Environment Canterbury
Regional Council
Kaunihera Taiao ki Waitaha

TECHNICAL REPORT Investigations and Monitoring Group

Effects of Lake Ellesmere (Te Waihora) openings on the coastal environment of Banks Peninsula

Report No. R12/84
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Report prepared for Environment Canterbury by

NIWA

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Taihoro Nukurangi

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Prepared for Environment Canterbury

August 2012

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Cover image (courtesy Graham Fenwick, NIWA):

Plumes from the Ashburton River sequentially displaced by tides and currents produced this remarkable pattern within nearshore waters of the Canterbury Bight.

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Reviewed by

John Zeldis

Approved for release by

Charles Pearson

Executive summary

Environment Canterbury manages water levels of Lake Ellesmere (Te Waihora) on behalf of the community through mouth openings. These discharges of conspicuously coloured lake water, with their low salinities, and high nutrient and sediment loadings, may affect coastal water quality and are perceived to impact multiple human values (mahinga kai, aquaculture, fisheries, tourism, and recreation) in the Banks Peninsula area. Thus, Environment Canterbury continues to actively investigate the mixing and transport of freshwater and its associated contaminants entering Canterbury Bight.

In this report, NIWA provides Environment Canterbury with two sets of information.

1. First, modelling of Lake Ellesmere plumes (in conjunction with freshwater inputs from other major rivers of Canterbury, Otago and Southland) following lake openings at or near eight specified representative coastal sites around Banks Peninsula to provide an understanding of the coastlines exposed to freshwater influence, the likely degree of seawater dilution, and the durations and depths of this exposure at the specified sites.
2. Second, a desktop investigation to evaluate the likely impacts of this diluted seawater exposure on the benthic invertebrates and algae within the modelled area of exposure.

During openings, Lake Ellesmere discharges water at maximum estimated rates of 180 m^3/s, and mean rates of 132 m^3/s. For context, Lake Ellesmere's mean discharge during openings is 62.6% of the Rakaia's mean discharge (211 m^3/s at Fighting Hill), and just 4.5% of the Rakaia's peak flow (at flood, the Rakaia can discharge over 5600 m^3/s). Overall, Lake Ellesmere mean discharge during openings is 34.4% of the total mean discharge of Canterbury Bight rivers, 8.5% of the total mean discharge of all major south-eastern rivers of the South Island, and just 2.5% of the peak flow if all major south-eastern rivers of the South Island are at peak flood simultaneously.

Modelled results in this report confirmed previous modelling, which demonstrated that Banks Peninsula's southern coastal waters are diluted less by the Lake Ellesmere plume and over a smaller area than that of the combined riverine freshwater discharges from east coast rivers. It also confirmed that dilution of Banks Peninsula coastal water by Lake Ellesmere water extends no deeper than that resulting from naturally-driven outflows of freshwaters from other sources within Canterbury Bight. The modelling further indicated that the lake's freshwater dilution plume may extend around the peninsula as far as Putakolo Head (Hickory Bay), diluting surface coastal waters (34–35 ppt) eastward to this point by up to c. 4–7% (to c. 31 ppt). Surface waters at the entrance to Akaroa Harbour were diluted to this extent, surface water at the middle Akaroa Harbour station was diluted very slightly (reduced by 1–3 ppt), and the inner station was not affected. The results also indicated that this dilution was generally confined to the surface 1–5 m of the water column, below which salinities were c. 34 ppt (close to full-strength seawater).

A substantial search of literature on experiments and/or detailed field investigations determined indicative salinity minima for several species (or closely related taxa) inhabiting sheltered to open shores on Banks Peninsula. These results indicated that most species tolerate 30 ppt seawater, and that many invertebrates, including rock lobsters (koura), farmed salmon and algae withstand even greater dilutions (down to 25 ppt). Survival of longer-term (10–40 day) exposures to these salinities is generally uncertain. Even during longer durations, however, biota inhabiting mid tide to sub-littoral depths will be inundated by potentially higher salinity water at least for a few hours daily during high tides (i.e., increased tidal water depth). Upper littoral algae and invertebrates are generally euryhaline, tolerating a far wider salinity range. Larger mobile invertebrates and fishes are expected to actively migrate away from low salinity waters, generally by moving to a greater depth. Despite this, there is some evidence that rock lobsters are exposed to diluted seawater at times, but modelling indicates that natural discharges from the Rakaia and other rivers south of Banks Peninsula produce greater dilution to a greater depth and, therefore, would have a relatively greater impact (if any) on the benthic biota.

In conclusion, following Lake Ellesmere lake openings, Banks Peninsula coastal waters are diluted to a lesser degree and over a smaller area than that caused by the combined natural riverine freshwater discharges from east coast South Island rivers. Modelling indicated that salinity-reductions of outer

coast of Banks Peninsula waters caused by Lake Ellesmere freshwater plumes are unlikely to significantly affect benthic invertebrates, farmed salmon and algae. Modelled plume dynamics and available knowledge also indicates that Lake Ellesmere plumes contribute little to concentrations of nutrients, entrained faecal indicator bacteria or toxic cyanobacteria in Banks Peninsula's coastal waters. However, the dynamics of nutrients and contaminants within Lake Ellesmere plumes, specifically water column stratification and phytoplankton productivity, would benefit from further investigation

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1 Introduction

1.1 Background

Environment Canterbury has statutory responsibility for a number of activities in the Canterbury region, including those relating to discharges into the coastal environment, and management of water quality, quantity and ecosystems in contributing catchments. As such, some potential conflicts between areas and stakeholders may arise, especially when coastal discharges carry elevated loadings of nutrients, sediments or other contaminants from land use or other activities. Environment Canterbury manages water levels of Lake Ellesmere (Te Waihora) on behalf of the community through mechanical openings of Kaitorete Spit at Taumutu. The associated discharges of conspicuously coloured lake water, with their high nutrient and sediment loadings, may affect coastal water quality, and are perceived to impact multiple human values (mahinga kai, aquaculture, fisheries, tourism and recreation), especially in the vicinity of Akaroa Harbour. Thus, Environment Canterbury continues to investigate the mixing and transport of freshwater and associated contaminants/nutrients entering the Canterbury Bight.

One of the first investigations of Lake Ellesmere plume impacts found no evidence to support anecdotal reports of lake water discharges inducing reduced catch rates for commercial rock lobster fisheries, although anecdotally reported symptoms for individual rock lobsters did match those found in seawater dilution experiments (Fenwick and Image 2002). Other anecdotal reports suggested that lake openings induced nuisance plankton blooms that interfered with commercial aquaculture and recreational shellfish harvesting activities in Akaroa Harbour, but no objective assessment has been carried out.

Remote-sensing studies showed that freshwater inputs from Canterbury Bight reached southern Banks Peninsula. Two studies (Schwarz 2008; Schwarz et al. 2010) found that freshwater plumes from Lake Ellesmere and Canterbury Bight rivers frequently reached the shores of Banks Peninsula, potentially penetrating well into Akaroa Harbour. These plumes typically moved north-eastward along the coast, around Banks Peninsula and into Pegasus Bay. River plumes were generally constrained to within c. 6km of the coast, but the more conspicuous yellow-green coloured plumes from Lake Ellesmere were distinguishable up to 33km offshore and up to 95km northeast and 27km southwest of the source.

A subsequent hydrodynamic study (Hadfield and Zeldis 2012) modelled freshwater plumes from the major rivers of Canterbury (including the Waimakariri to the north of Banks Peninsula), Otago and Southland (and Lake Ellesmere). The modelled results were physically plausible and qualitatively consistent with the remote sensing results and in-situ data. Modelled river plumes were initially 10–30% (but up to 100%) freshwater in concentration and shallow (typically 1–3 m deep). They were progressively diluted by vertical mixing and horizontal dispersion, to form a coastal band c. 10 km wide with surface freshwater concentrations typically 5–10%. Freshwater concentrations were substantially higher on the southern and eastern sides of Banks Peninsula than on the northern side.

Given the extent to which these riverine and lake water plumes persisted and extended around Banks Peninsula's coastline, there was obvious concern for their impact on coastal biota, notably mahinga kai, and recreational and aquaculture species. Salinity is one the major determinants of species distributions in coastal waters, especially in the intertidal and sub-tidal zones. Thus, freshwater inputs from Canterbury Bight sources may have significant influence on the coastal ecosystem of Banks Peninsula indicating a need to assess the potential impacts of Lake Ellesmere discharges (in context with other Canterbury Bight freshwater sources) on biodiversity and human values in the Banks Peninsula coastal area.

1.2 This project

Environment Canterbury requires an assessment of the potential impacts of Lake Ellesmere discharges on Banks Peninsula's ecological and human values to inform its resource consent applications to manage lake levels via artificial lake openings. This report provides Environment Canterbury with two sets of information for this purpose.

1. Modelling of Lake Ellesmere plumes (in conjunction with freshwater inputs of other major rivers of Canterbury, Otago and Southland) at an appropriate spatial scale to provide an understanding of the coastline areas exposed to freshwater influence, the likely degree of seawater dilution, and the durations and depths of this exposure at selected sites around Banks Peninsula. Model-based estimates are made at or near eight specified representative coastal sites (Section 1.1) around Banks Peninsula of the concentration of freshwater from Lake Ellesmere, as a function of time relative to lake opening events and depth.
2. A desktop investigation to assess the likely impacts of this diluted seawater exposure on the benthic invertebrates, farmed salmon and algae within the area of exposure. This assessment relies on existing information on salinity/freshwater tolerances and/or the estuarine persistence of representative species within key groups. It focusses mainly on mahinga kai and aquaculture species, and also on other more common shore species (discussed further in Section 1.2).

Discussion with Environment Canterbury revealed that fine-scale hydrodynamic modelling of Lake Ellesmere freshwater plumes at numerous coastal sites over relatively long time-frames (i.e. decadal) is not required. In addition, we recognise a general paucity of information on freshwater/contaminant effects on biota of interest around Banks Peninsula, scant baseline ecological knowledge of the area and no marine water quality measures co-incident with lake openings. This information gap precludes direct assessments of ecological effects associated with freshwater plumes derived from Lake Ellesmere.

2 Methods

1.1 Hydrodynamic modelling

Eight representative sites of interest around coastal Banks Peninsula were selected by Environment Canterbury in March 2012 (Figure 1, Table 1) during discussions with NIWA. Model-based estimates were made at these sites of the concentration of freshwater from Lake Ellesmere (in conjunction with hydraulic-forcing from other major rivers of Canterbury, Otago and Southland) as a function of time, relative to historical lake opening events. For a detailed description of the modelling system, see Hadfield and Zeldis (2012).

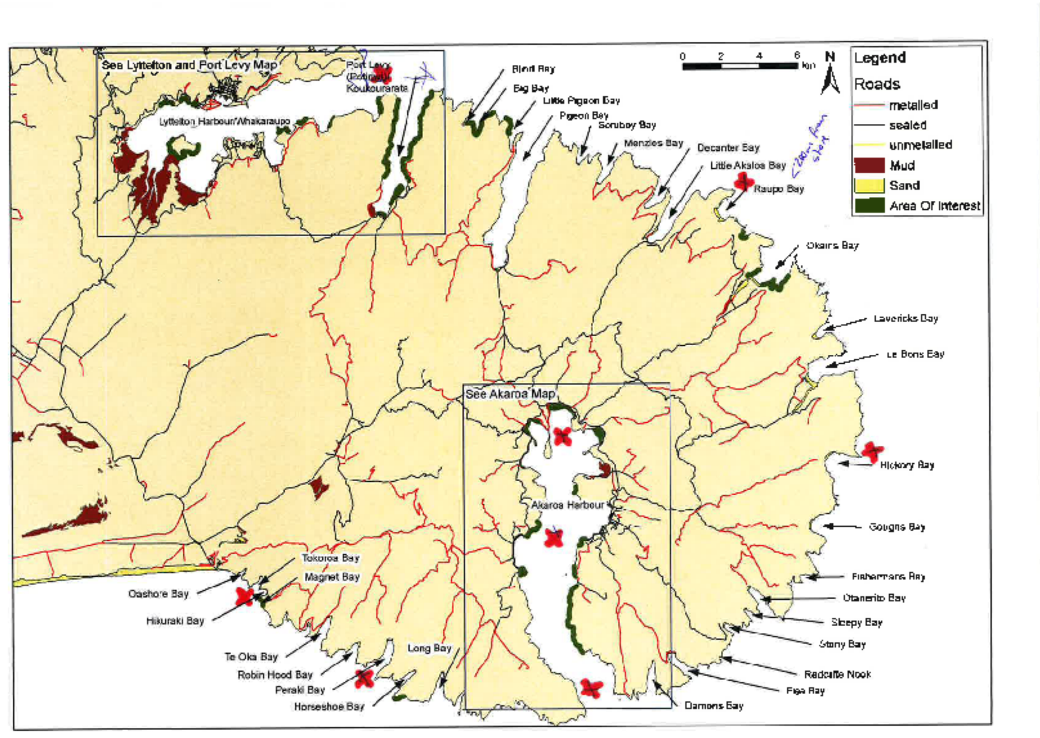

Figure 1: **Representative coastal sites of interest (marked by red crosses) as indicated to NIWA by Environment Canterbury (March 2012)**

Table 1: **Representative coastal sites of interest identified by Environment Canterbury**

	Site of interest	Location
1	Tokoroa Bay	172.7317°E, -43.8382°S
2	Peraki Bay	172.8083°E, -43.8773°S
3	Akaroa Harbour entrance	172.9575°E, -43.8877°S
4	Akaroa Middle	172.9287°E, -43.8156°S
5	Akaroa Inner	172.9391°E, -43.7703°S
6	Putakolo Head	173.1364°E, -43.7767°S
7	Long Lookout Point	173.0495°E, -43.6471°S
8	Lyttelton Harbour entrance	172.8183°E, -43.5946°S

A two-stage approach has been taken to the modelling of Lake Ellesmere freshwater. The first stage was to analyse two previous simulations (Hadfield and Zeldis 2012). The model used a set of nested grids (refer to Hadfield and Zeldis 2012), and for these two simulations the inner grid had a horizontal spacing of 1000 m. The results of these simulations presented in a draft version of this report have now been superseded by the results from the second modelling stage, described below.

For the second stage, the model was run for three periods (Figure 2) of 175, 175 and 275 days, respectively, bracketing a total of nine Lake Ellesmere openings. Note that, because of the influence of wind on the movement of the freshwater, we expect that different lake openings will have different signatures at the sites around Banks Peninsula. The results below confirm this expectation. Sites were specified on the model grid as close as possible to the ones shown in Figure 1. Time series of the concentration of freshwater derived from Lake Ellesmere were extracted and are related to Lake Ellesmere lake openings below (Section 3.2).

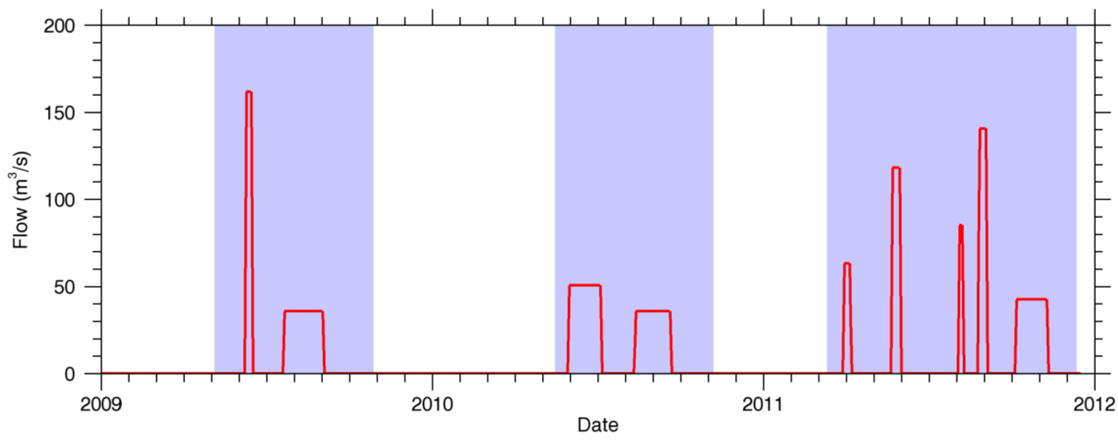

Figure 2: **Lake Ellesmere (Te Waihora) flow vs modelled periods.** Flow rate is indicated in red and periods for which the hydrodynamic model has been run are shaded in light purple

There were two sets of runs, one on the original 1000 m grid and another on a 500 m grid that was set up for the present project (simulations on the finer grid are substantially more expensive in terms of computer time than on the coarser grid, so we did not attempt them until the first stage had been analysed and the design of the second stage finalised). We compared the 1000 m and 500 m results and found them to be similar, except that peak concentrations near to the river sources are somewhat higher with the finer grid. We therefore consider the 500 m results to be superior and these are the only ones shown in this report.

Regarding processes that are important near the coast, the model lacks freshwater inputs other than the major rivers of Canterbury, Otago and Southland, and so will not produce estuarine circulations in the bays and harbours. However, it does include tides and, therefore, generates tidal flows in and out of the bays and harbours, with an accuracy that is limited by the representation of the topography. Other processes that might affect freshwater concentrations near the coast are missing from the model, including micro-scale wind flows steered by the local topography and wave-induced vertical mixing in shallow waters. It is not possible to quantify the effects of these processes without a detailed validation study involving a major field measurement component. However, the model should predict freshwater concentrations a few hundred metres offshore from the coast of Banks Peninsula reasonably well.

1.2 Likely ecological impacts of dilution by freshwaters

A list of common intertidal organisms, including mahinga kai, was developed from published papers and unpublished reports of investigations around Banks Peninsula. Because the literature potentially relevant to this topic is so large, the primary focus was on mahinga kai species, commercial fisheries and aquaculture species. Some of the more conspicuous and ecologically important sessile to relatively sedentary shore organisms (i.e., those unable to move away from pulses of diluted seawater) were also included as surrogates for the biota overall.

Desktop searches of available literature were then used to determine salinity[1] tolerances of the selected species to periodic exposure to diluted seawater. Searches were conducted by accessing peer-reviewed scientific publications, technical reports and unpublished datasets. We identified these resources by querying literature datasets (e.g., ISI Web of Science; Google Scholar), direct contact with relevant specialists within NIWA, and from within our own collection of relevant unpublished information in this field. Experimental evidence of salinity tolerances are lacking for many of the species we identified, so reported distributions, notably along the natural gradients within harbours and estuaries, were used to develop putative assessments of salinity tolerances. These salinity tolerance assessments were peer-reviewed by two experienced marine ecologists, and, in the few cases where understandings of salinity tolerances differed, these were reviewed using further published information to arrive at a consensus.

Next, modelled freshwater dilutions and durations of dilution were compared to predictions of those occurring along Banks Peninsula's southern coast under the prevailing lake openings regime. Where appreciable differences in salinities and durations of dilutions were predicted, the likely impacts of dilution by Lake Ellesmere openings on these organisms along Banks Peninsula and within Akaroa Harbour were assessed against their salinity tolerances. Based on these assessments, some more general evaluations of the potential ecological impacts of freshwater plumes from Lake Ellesmere were made.

The assessment was constrained to the direct effects (e.g., mortality, species distribution) of these freshwater dilution pulses. Resources did not allow any attempt to evaluate wider-scale indirect ecological impacts (e.g., altered trophic webs, long-term organism fitness etc.) of reduced salinity within these freshwater pulses or the impacts of elevated nutrients, freshwater phytoplankton, micro-organisms, sediments, or other contaminants entrained within freshwater pulses. However, in the Discussion section of this report, we do provide comment on the latter in light of available information, as well as on the applicability of hydrodynamic modelling for potential future elucidation of such factors associated with Lake Ellesmere freshwater pulses.

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[1] Salinity is the saltiness or dissolved salt content of a body of water. It is a general term used to describe the levels of different salts such as sodium chloride, magnesium sulphate, calcium sulphate and bicarbonates in seawater. In oceanography, salinity has traditionally been expressed as parts per thousand (ppt or ‰), which is approximately grams of salt per kilogram of solution. In 1978, oceanographers redefined salinity in the Practical Salinity Scale (PSS), as the conductivity ratio of a sea water sample to a standard KCl solution (Lewis 1980; Lewis and Perkins 1981). Although PSS is a dimensionless quantity, its "unit" is usually called psu. The salinity in psu generally does not exactly equal the salinity in ppt. As the majority of the pertinent information we sourced for this report refers to salinity in terms of ppt, we will use this as the measure of salinity in this report.

3 Results

3.1 Freshwater inputs into northern Canterbury Bight

Freshwater from rivers on the south east coast of the South Island discharging into Canterbury Bight tends to flow north-eastward adjacent to the coast and impinge on the south coast of Banks Peninsula (Schwarz 2008; Schwarz et al. 2010; Hadfield and Zeldis 2012). The rivers include the Ashburton (mean discharge 25 m^3/s), Rangitata (123 m^3/s), Opihi (25 m^3/s) and Rakaia (211 m^3/s). Thus, Canterbury Bight rivers can contribute c. 384 m^3/s of river water, on average to dilute coastal seawater around Banks Peninsula. Rivers further south (notably the Clutha and Waitaki) discharge a combined 1190 m^3/s on average, much of which also enters Canterbury Bight and passes around Banks Peninsula (Hadfield and Zeldis 2012). If all these south-eastern South Island rivers are considered, they could potentially contribute some 1550 m^3/s of river water, on average, and c. 10,000 m^3/s at peak flood, simultaneously, to potentially dilute coastal seawater around Banks Peninsula

Between 12 September 1990 and 1 July 2002, Lake Ellesmere was open 47 times for a total of 769 days (Environment Canterbury unpublished data, sourced for Fenwick and Image 2002). The number of days per opening varied from 1 to 79 (mean 16.7) and the mean number of days open per year was 65, or 17.8% of the time. Horrell (2008) measured flows during one opening of Lake Ellesmere in June 2008 and used these data to derive a post-opening flow pattern. Outflows increased then decreased over the first 11–12 days after opening, inflows more or less equalled outflows over the next 1–2 days, a net inflow for 1–2 days followed, before c. 25 days of no flows, except a few days when sea conditions pushed high tidal water across the newly developed berm into the lake. Maximum estimated outflow was 250 m^3/s, but highest mean daily outflows during the first 12 days of that opening were estimated at 180 m^3/s after taking tidal changes into account, with a mean outflow of 132 m^3/s (Horrell 2008, Figure 17). However, as outflow/inflow patterns for Lake Ellesmere have not been consistently measured, and will be highly variable temporally according to factors such as lake level prior to opening, prevailing winds, tides, sea surge/swell and height of the beach barrier (Horrell 2008), we have used a constant flow pattern in our modelling.

To put Lake Ellesmere freshwater discharges into context, its mean discharge during openings is 62.6% of the Rakaia River's mean discharge (211 m^3/s at Fighting Hill), 38.5% of the mean freshwater discharge from both sources and just 4.5% of the Rakaia River's peak flow (at flood, the Rakaia River can discharge over 5600 m^3/s (averaged over a tidal cycle)). The Rakaia's discharge exceeds 300 m^3/s c. 14% of the time and Lake Ellesmere's peak 40% of the time (NIWA unpublished data), whilst Lake Ellesmere was open just c. 18% of the time over Sept 1990–July 2002. Overall, Lake Ellesmere's mean discharge during openings is 34.4% of the total mean discharge of Canterbury Bight rivers, 8.5% of the total mean discharge of all major south-eastern rivers of the South Island, and just 2.5% of the peak flow if all major south-eastern rivers of the South Island are at peak flood, simultaneously.

3.2 Hydrodynamic and dispersion modelling

The first series of figures below (Figure 3 to Figure 5) shows time series of concentration of freshwater derived from Lake Ellesmere at the eight sites of interest (Table 1), as simulated by the hydrodynamic model, along with Lake Ellesmere flow rate (cf. Figure 2). Note that the freshwater concentration presented and discussed here is evaluated by labelling the inflow (in the model) from Lake Ellesmere with a tracer. That tracer is assigned the value 1 in the inflowing water and is initially 0 in the sea, so its concentration can be interpreted as the volume fraction of Lake Ellesmere water. In the simulations described here there were eight such tracers labelling different rivers or groups of rivers (Hadfield and Zeldis 2012 Table 1). Labelling the sources in this way means that the contribution of the different rivers can be distinguished. It also makes it possible to distinguish small changes in freshwater concentration from background salinity variations. A freshwater concentration of 10% corresponds to a salinity depression of 3.5 ppt.

Each of the first three sites along the coast (Figure 3) experiences a discernible pulse – or set of pulses – following each lake opening event, but the relationship between the lake opening event and the pulse it produces is highly variable. In particular, the opening events with durations exceeding 30 days do not produce similarly sustained pulses in freshwater concentration. The maximum freshwater concentration decreases with increasing distance from Lake Ellesmere, and the highest concentration is 22% (27 ppt) at Site 1, Tokoroa Bay. The delay between the beginning of the opening event and the arrival of freshwater is variable, but not less than five days. Interestingly, when the freshwater does arrive it often arrives at all three sites at roughly the same time. This may well occur because freshwater moves along the coast in wind-driven bursts (e.g., see the animations accompanying Hadfield and Zeldis (2012)) and, when these occur, they are quite rapid.

At the two sites within Akaroa Harbour (Figure 4) the freshwater concentrations are much lower (maximum 1.5% at Site 4 and 1% at Site 5) and the freshwater that does reach these sites persists for a long time.

For perspective on these modelled salinity depressions for Akaroa Harbour, we made a preliminary evaluation of NIWA CTD (conductivity, temperature, depth) data recorded from several stations along the midline of Akaroa Harbour on nine occasions over 30 October 1996 to 12 December 1998. The CTD data indicated that, on most sampling dates, the water column was unstratified with respect to salinity, with surface salinities at or close to full oceanic seawater (34–35 ppt). However, surface salinities can become markedly reduced on occasion. For example, on 30 January 1997 surface waters were significantly diluted in an area extending from 1 to 2 km outside the heads to its upper reaches (close to Onawe Peninsula). Salinities at the surface (0.3 m depth) were markedly reduced (<20 ppt) at all but four of the 16 stations sampled at this time; the salinity was below 10 ppt for nine stations, below 14 ppt for two stations and at 20 ppt for another. Salinity profiles during this event were broadly similar at all stratified stations: markedly reduced salinities at 0.3 m depth, near-full salinities at 0.8 m depth and essentially full seawater (34.2 ppt) at 1.3 m depth. Salinities measured 0.5 m above the bottom were consistently high (34.5–34.6 ppt) at all stations.

At the three sites on the eastern and northern sides of Banks Peninsula (Figure 5), the freshwater concentrations were much lower than they are on the southern side of the peninsula. As one moves around Banks Peninsula away from Lake Ellesmere, the maximum freshwater concentration drops and the pulse following each lake opening becomes more delayed and persists longer.

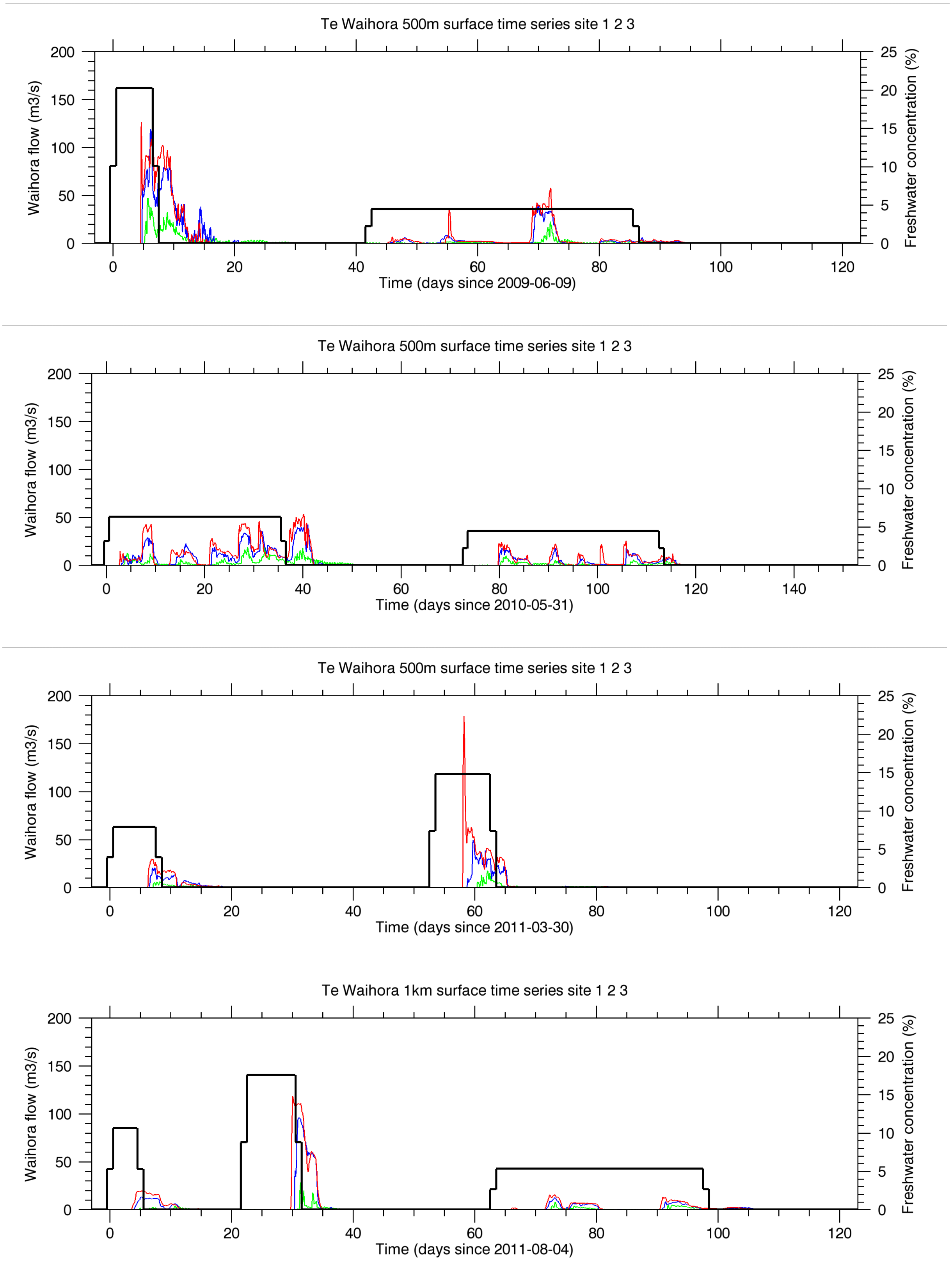

Figure 3: **Surface concentration of Lake Ellesmere (Te Waihora) freshwater at sites 1–3.** Surface concentration of freshwater derived from Lake Ellesmere (right-hand axis) at sites 1 (Tokoroa Bay, red), 2 (Peraki Bay, blue) and 3 (Akaroa Entrance, green) with Lake Ellesmere flow (black, left-hand axis) for four periods spanning the Ellesmere opening events

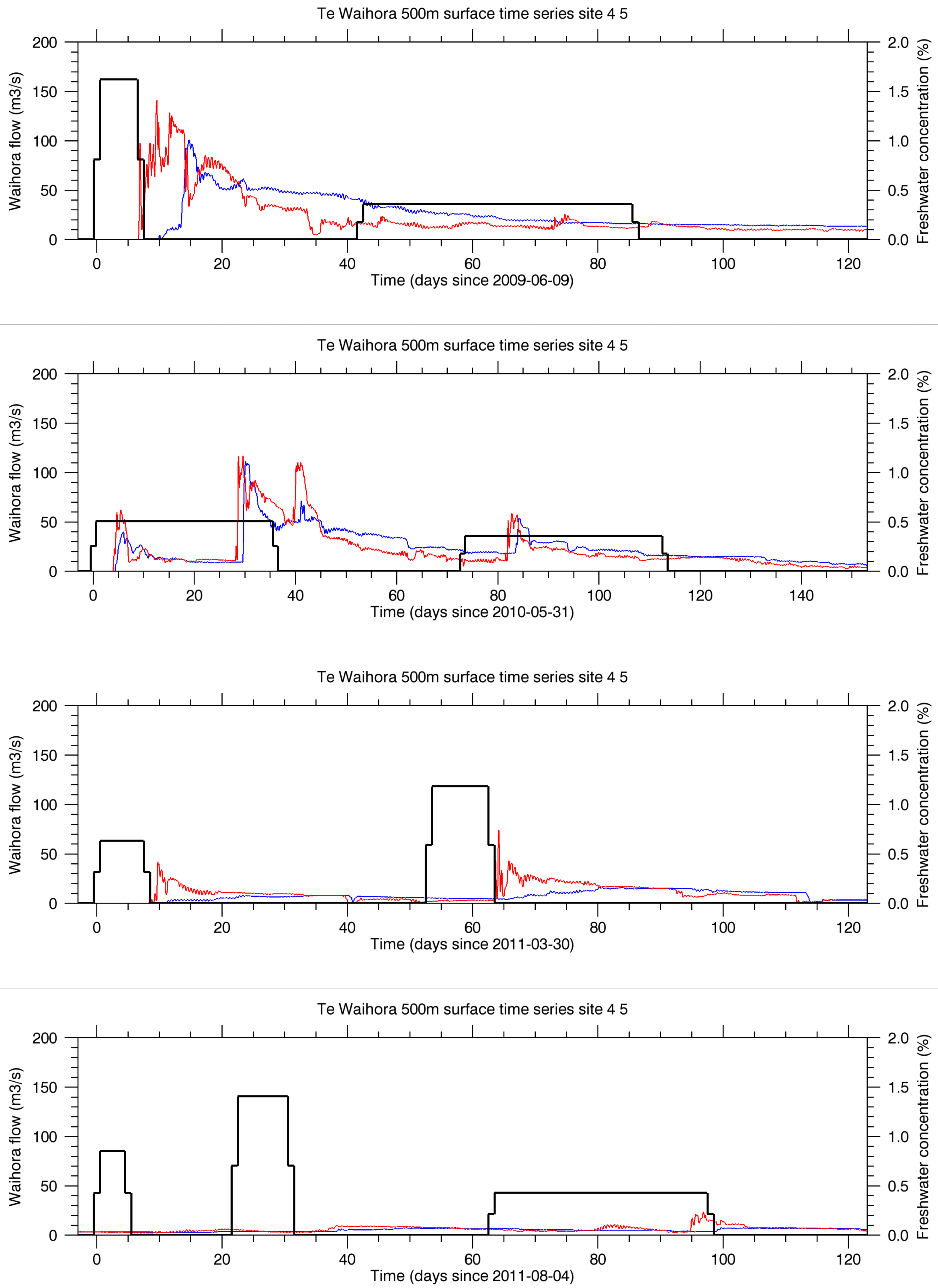

Figure 4: **Surface concentration of Lake Ellesmere (Te Waihora) freshwater at sites 4 and 5.** Surface concentration of freshwater derived from Lake Ellesmere (right-hand axis) at sites 4 (Akaroa Middle, red), and 5 (Akaroa Inner, blue) with Lake Ellesmere flow (black, left-hand axis) for four periods spanning the Ellesmere opening events

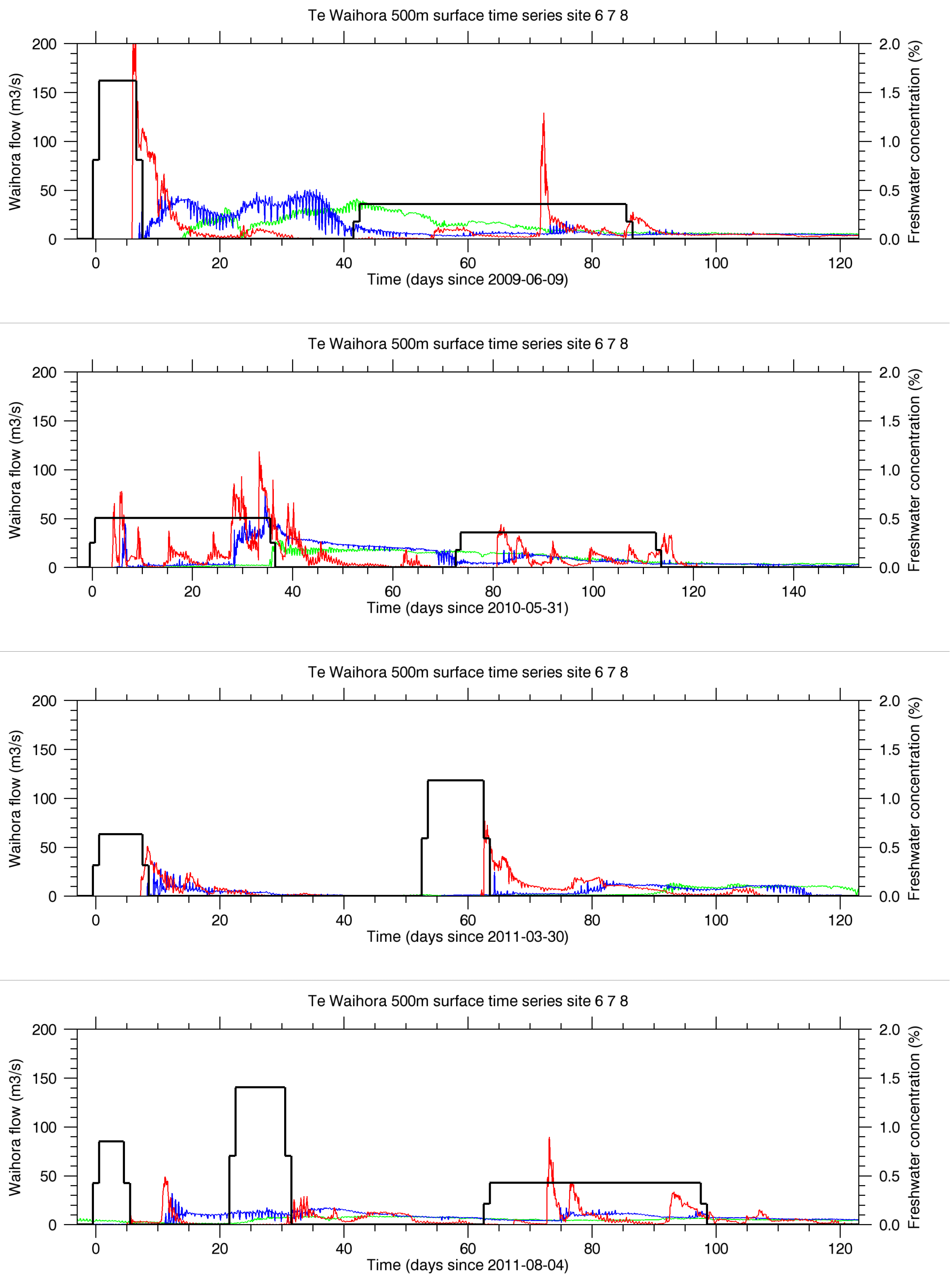

Figure 5: **Surface concentration of Lake Ellesmere (Te Waihora) freshwater at sites 6–8.** Surface concentration of freshwater derived from Lake Ellesmere (right-hand axis) at sites 6 (Putakolo Head, red), 7 (Long Lookout Point, blue) and 8 (Lyttelton Harbour entrance, green) with Lake Ellesmere flow (black, left-hand axis) for four periods spanning the Ellesmere opening events

The next series of figures below (Figure 6 to Figure 8) gives an indication of how the concentration of freshwater from Lake Ellesmere varies with depth. The profiles show the 99th percentile concentration (to characterise the high dilution events) at each model depth taken over all three simulations. Note that the time series of Lake Ellesmere discharges is quite variable, as is the shape of the freshwater pulses they produce, so, if one evaluated the same statistics from a different set of periods, they would probably be different; the figure is intended to give a general idea of the vertical variation rather than any specific pattern.

At Sites 1–3 along the coast (Figure 6) the profiles all drop off with depth. The freshwater is generally concentrated in the top 5–10 m of the water column.

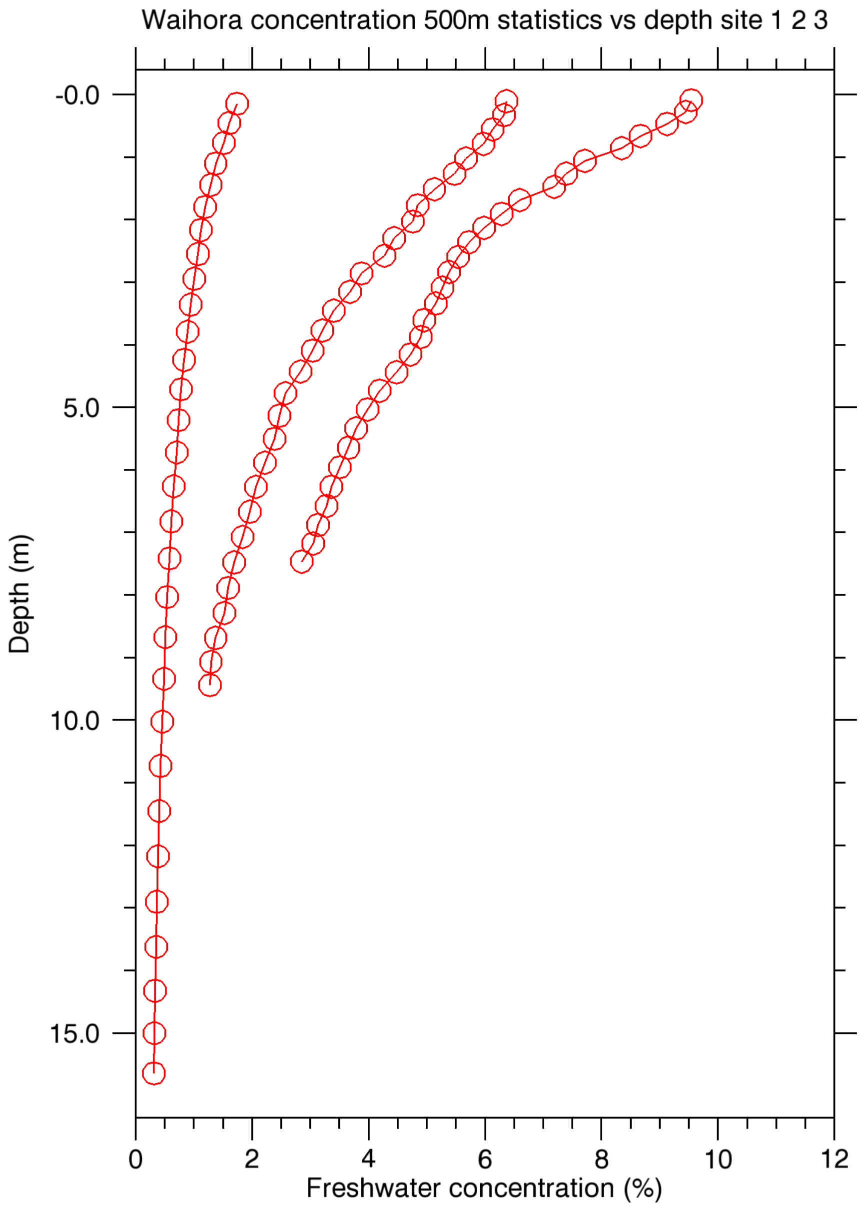

Figure 6: Profiles of freshwater statistics at Sites 1–3. Profiles of 99th percentile (left-hand curve) concentrations of Lake Ellesmere freshwater at sites 1 (Tokoroa Bay, right), 2 (Peraki Bay, centre) and 3 (Akaroa Entrance, left)

At Sites 4 and 5 within Akaroa Harbour (Figure 7), the profiles show relatively little variation with depth. This does not match the limited observations we have of freshwater incursions into Akaroa Harbour (as described earlier). However, as noted above, the model was not expected to resolve processes in the harbour very well.

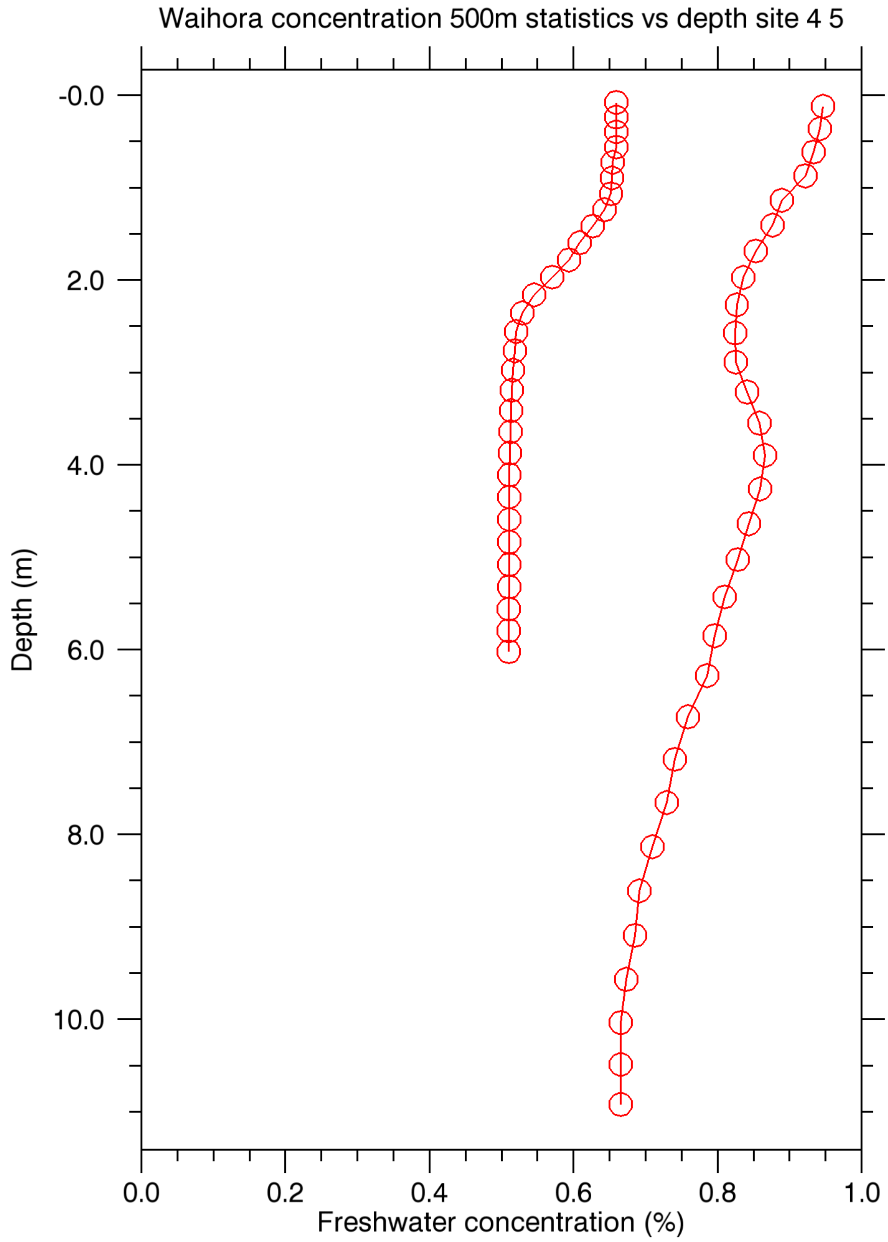

Figure 7: **Profiles of freshwater statistics at Sites 4-5.** Profiles of 99th percentile (left-hand curve) concentrations of Lake Ellesmere freshwater at sites 4 (Akaroa Middle, right) and 5 (Akaroa Inner, left)

At Site 6 the freshwater profile is moderately enhanced at the surface and at Sites 7 and 8 it is vertically uniform (Figure 8). This is consistent with the freshwater plume being vertically mixed (probably by episodic wind events) as it moves away from the source.

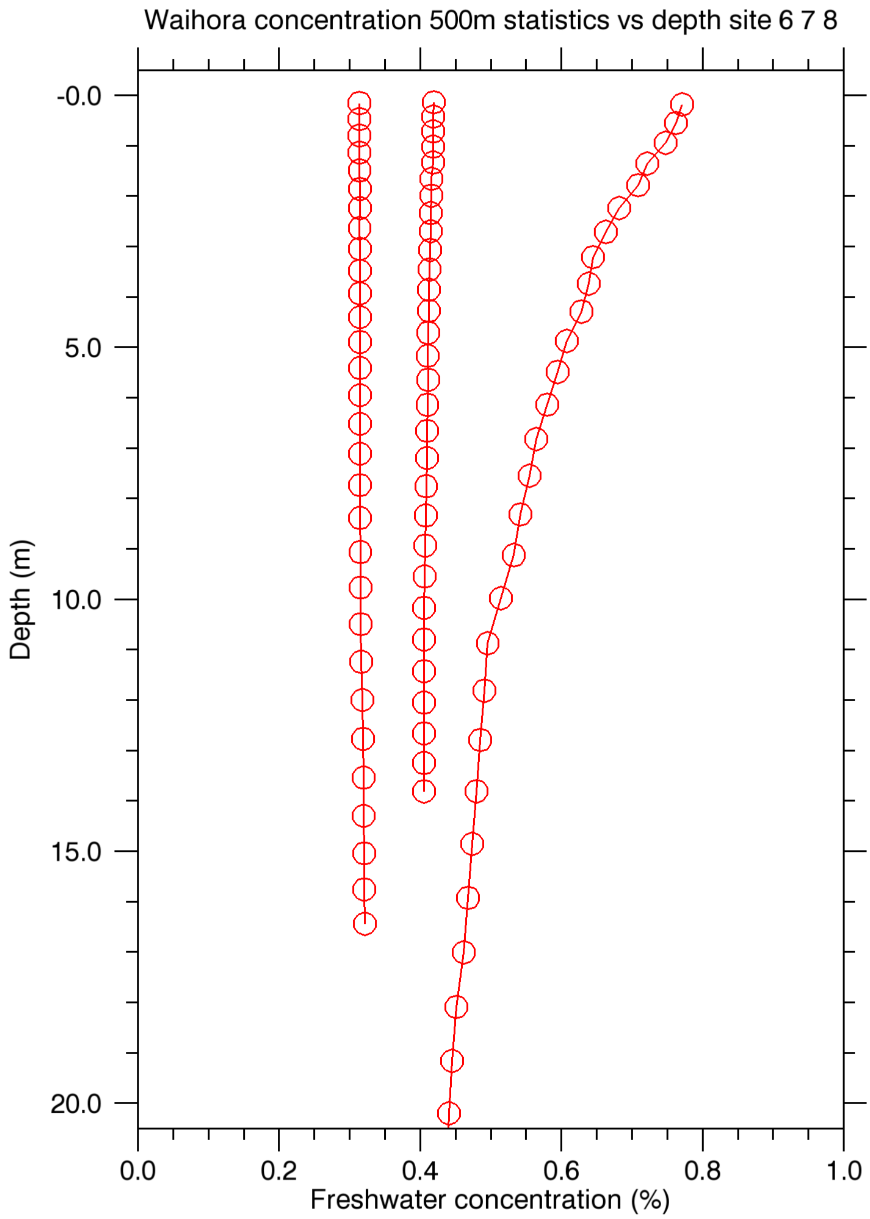

Figure 8: **Profiles of freshwater statistics at Sites 6-8.** Profiles of 99th percentile (left-hand curve) concentrations of Lake Ellesmere freshwater at sites 6 (Putakolo Head, right), 7 (Long Lookout Point, centre) and 8 (Lyttelton Harbour Entrance

For an indication of the relative concentrations of freshwater from Lake Ellesmere and the Rakaia River, Figure 9 to Figure 11) show time series of the surface concentration of freshwater derived from these two sources, for the same periods as Figure 3 to Figure 5. Rakaia River freshwater usually predominates, even during openings of Lake Ellesmere. However, there are a couple of occasions at Site 1 (Figure 9) and also one at Site 3 (Figure 10) when elevated levels of Lake Ellesmere water was not matched by elevated levels of Rakaia water.

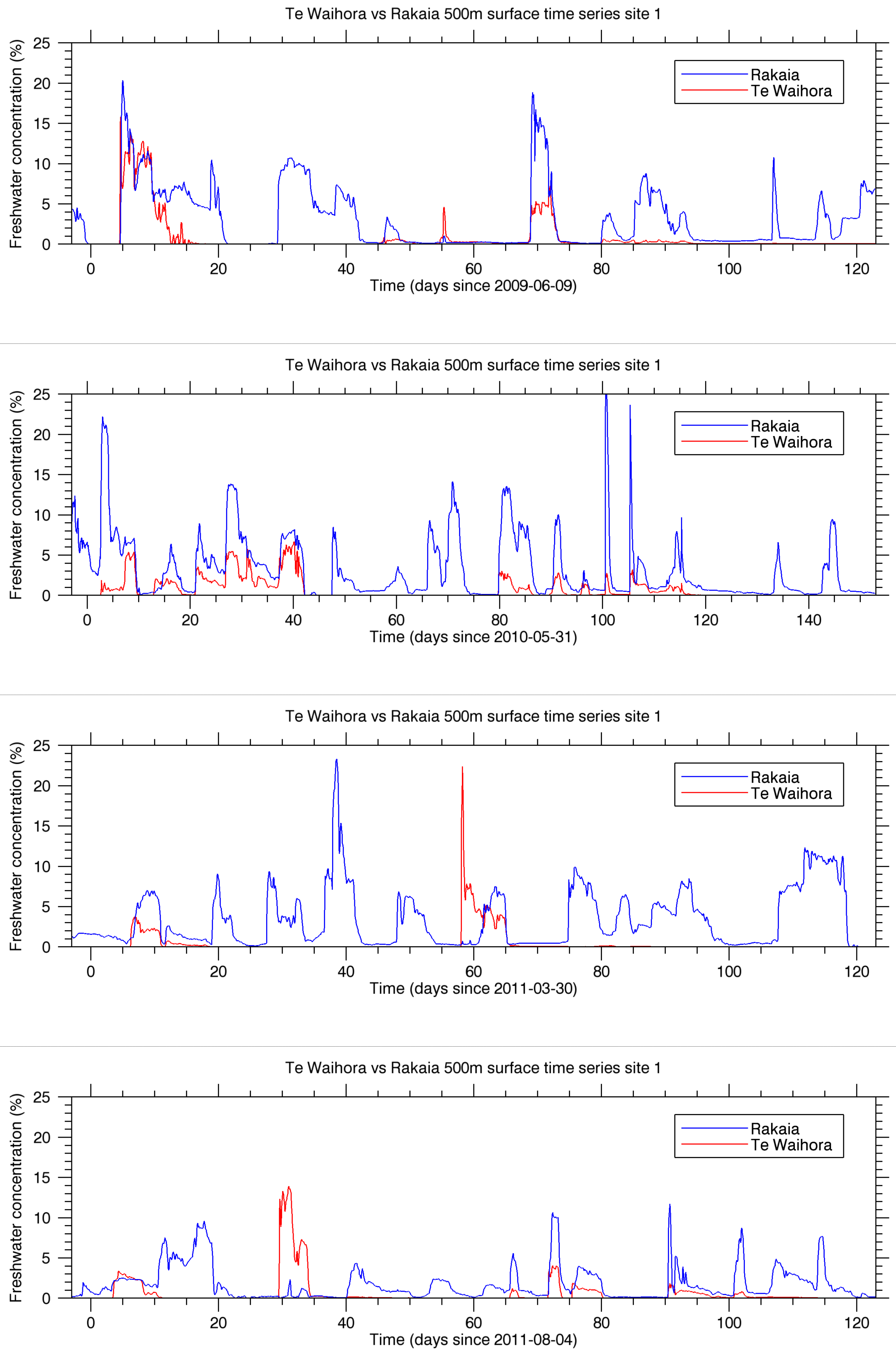

Figure 9: Surface concentration of Lake Ellesmere (Te Waihora) and Rakaia River freshwater at Site 1 .

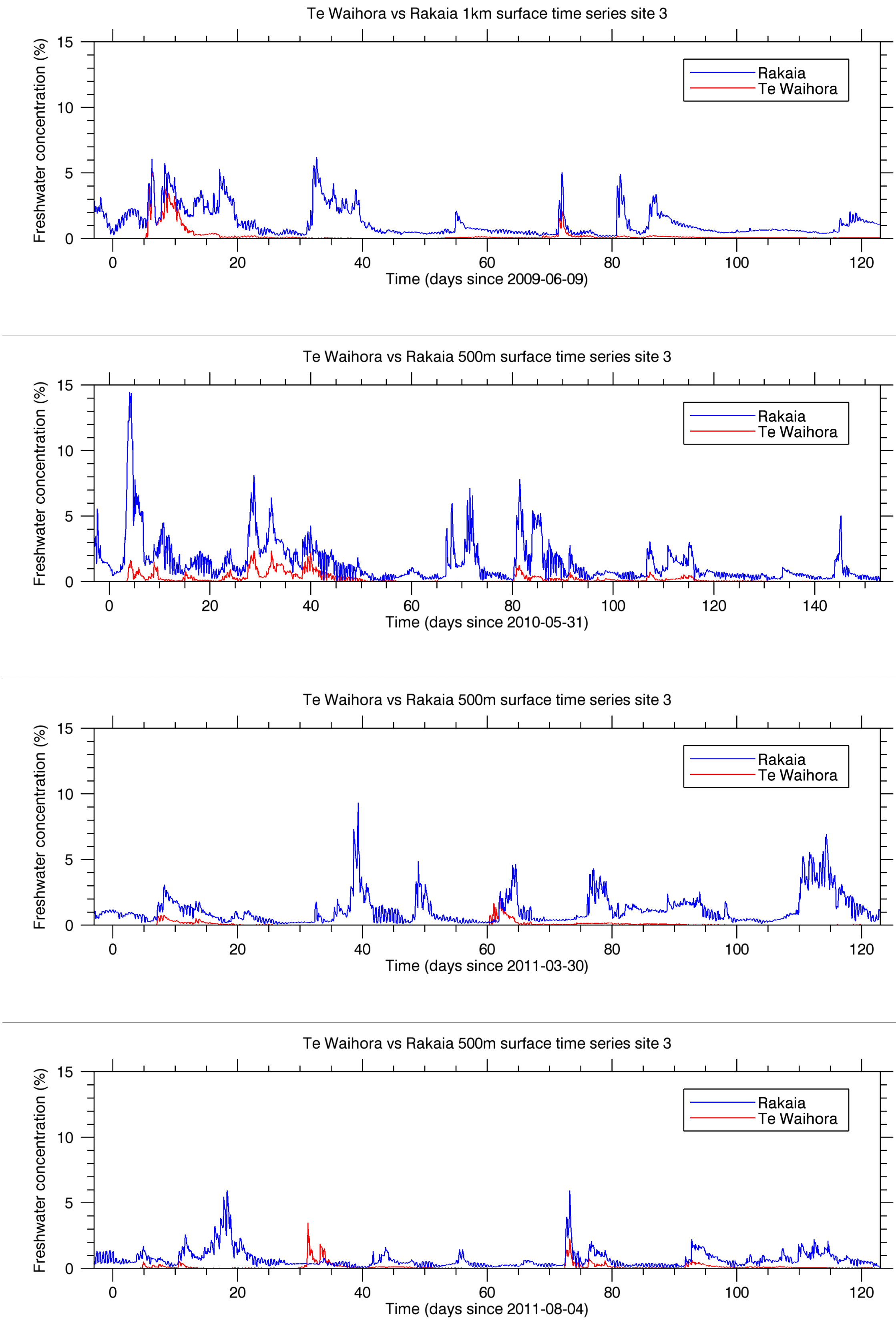

Figure 10: Surface concentration of Lake Ellesmere (Te Waihora) and Rakaia River freshwater at Site 3

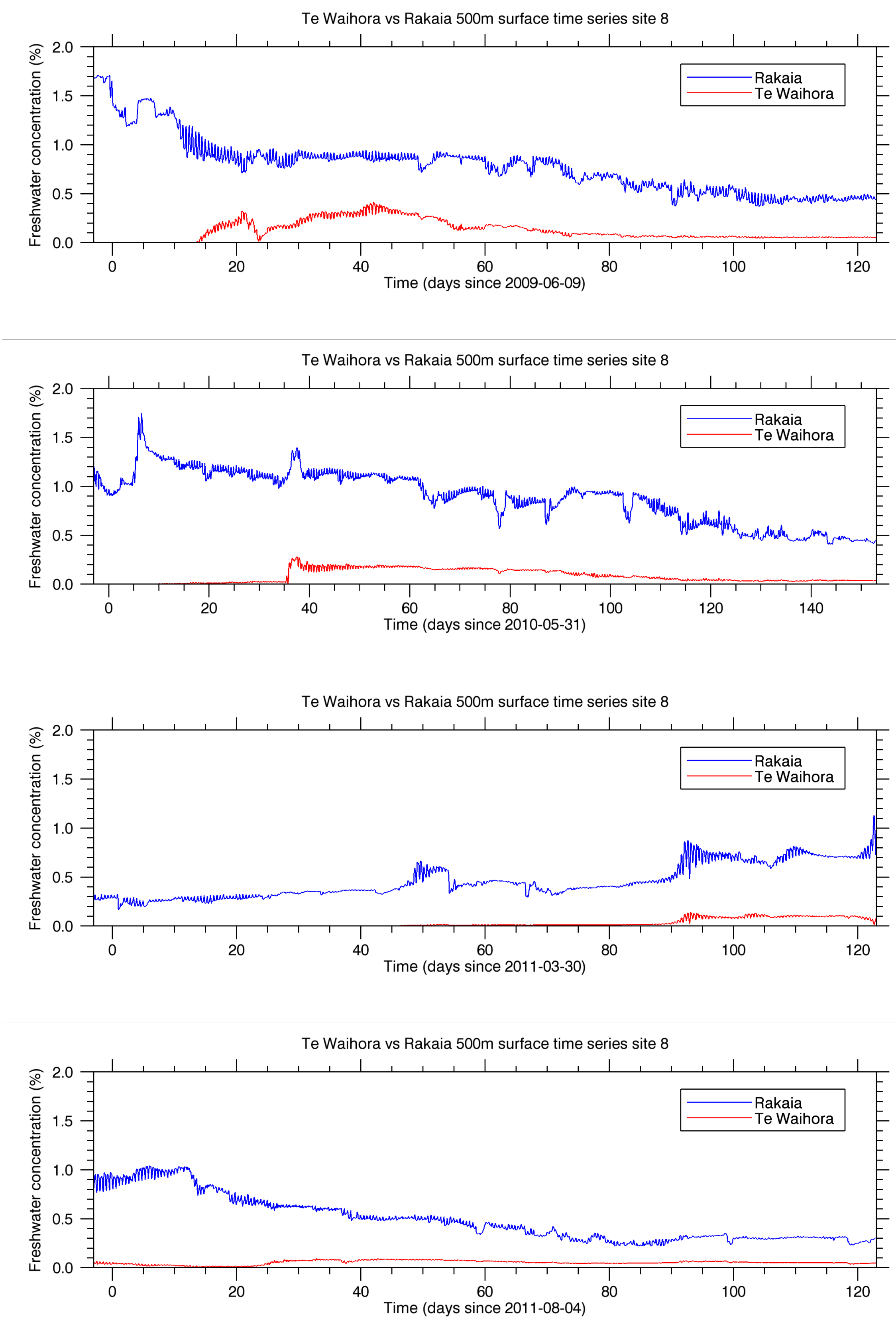

Figure 11: Surface concentration of Lake Ellesmere (Te Waihora) and Rakaia River freshwater at Site 8 .

3.3 Ecological impacts of salinity depression

Greatest ecological impacts from freshwater plumes associated with Lake Ellesmere openings are expected to be on intertidal biota along the southern coast of Banks Peninsula, especially the exposed to moderately exposed shores from the base of Kaitorete Spit to Akaroa Harbour. In its brief for the project, Environment Canterbury identified eight sites of interest encompassing the entire peninsula (Tokoroa Bay, Peraki Bay, Akaroa Head, Putakolo Head, Long Lookout Point, and Lyttelton Harbour entrance (Awaroa and Adderley Head), as well as increasingly sheltered environments within Akaroa Harbour (near Opukutahi and Green Point, Onawe and Duvauchelle Bay) (Figure 1, Table 1).

Salinity change, specifically reduced salinity with increased freshwater outflows from south-eastern rivers of the South Island and Lake Ellesmere, is expected to be the single most important effect on the peninsula's coastal ecology. However, salinity tolerances are known for few species. Observations of distributions with respect to measured salinities, and other observations, provide some information on likely salinity tolerances for assessing potential impacts for this investigation.

Because salinity tolerance information is lacking for most species inhabiting southern Banks Peninsula coasts, we treat those for which information is available as surrogates for the total biota. Our attention is focussed on intertidal and shallow sublittoral fringe species for two reasons. First, seawater dilution is likely to be greatest at the surface and over the upper 1–5 m of the water column because freshwater usually overlies denser, full seawater. Wave action speeds mixing, breaking down any salinity gradient and halocline (=strong, vertical salinity gradient within a body of water), but even partially mixed freshwater tends to overlie seawater, thus placing intertidal and sublittoral-fringe biota at greatest risk of exposure to reduced salinities. Second, salinity tolerances are generally much better understood for intertidal and estuarine organisms because they are naturally exposed to varying salinities during tidal and/or seasonal cycles. Thus, their degree of tolerance and the underlying physiological mechanisms have received significant research attention, providing some of the information essential to this evaluation.

3.3.1 Species included

Details of the intertidal biota of all of these areas were not available, but available evidence indicates that it is very similar to that on shores of equivalent wave exposure elsewhere on Banks Peninsula and the South Island (Knox 1953; Morton and Miller 1968; Fenwick and Ross 2002; Fenwick 2003; Fenwick 2004; Bolton-Ritchie 2005a). None of these studies, however, provides any information on salinity tolerances. Therefore, we have included species for which we have information on salinity tolerances from accounts of either their specific tolerances or, for some ecologically important species in the area, the tolerances of closely related taxa.

3.3.2 Salinity tolerances

Studies of marine communities in the highly stratified Doubtful Sound (Batham 1965; Grange et al. 1981; Witman and Grange 1998; Boyle et al. 2001) indicate the tolerances of several species to reduced salinities and their likely responses to any increased dilution resulting from changes to Lake Ellesmere openings regimes. In addition, we summarise relevant information on salinity tolerances of New Zealand species or genera to indicate the actual or likely salinity tolerances of species inhabiting Banks Peninsula shores (Table 2).

Table 2: **Likely *in-situ* seawater dilution tolerances for common Banks Peninsula shore organisms from literature or predicted from available information (sources in text on each species), and distribution changes in Doubtful Sound post-Manapouri power station. Seawater tolerances are expressed both in salinity (ppt) and in percent (%) freshwater, with the latter in brackets ()**

Species	Major group	Field seawater tolerance: salinity (ppt) and percent (%) freshwater	Experimental or other species' freshwater tolerances (10-20 °C, where available): salinity (ppt) and percent (%) freshwater	Batham (1965) zones	Boyle et al. (2001) zones
Ulva spp.	Algae: Chlorophyta	5–29 ppt (85.7–17.1%)?	5–40 ppt (85.7–(-)14.3%)?	II-IV	III-V
Hormosira banksii	Algae: Phaeophyta	30 ppt (14.3%)?	NA	I-V	VI
Macrocystis pyrifera	Algae: Phaeophyta	22 ppt (37.1%)	NA	nil	VI
Sargassum sinclairii	Algae: Phaeophyta	20 ppt (42.9%)?	12 ppt (65.7%) for 8 h every 12 h		
Durvillaea antarctica	Algae: Phaeophyta	30 ppt (14.3%)?	NA	VI	VI rare
Porphyra columbina	Algae: Rhodophyta	11 ppt (68.6%)	10–20 ppt (71.4–42.9%)	nil	V
Evechinus chloroticus	Echinodermata: Echinoidea	30 ppt (14.3%)	27.5 ppt (21.4%) 100% lethal after 48 h		
Patiriella regularis	Echinodermata: Asteroidea	5–12.5 ppt (85.7–64.3%)	NA		
Coscinasterias calcamaria	Echinodermata: Asteroidea	25 ppt (28.6%)	20 ppt (42.9%) 100% lethal after 29 h		
Pomatocerus caeruleus	Annelida: Polychaeta	5–12.5 ppt (85.7–64.3%)	NA	II, IV-V	I (rare)
Limnoperna pulex	Mollusca: Bivalvia	3–28 ppt (91.4–20%)	1–28 ppt (97.1–20%)	I-VI	V-VI
Mytilus galloprovincialis	Mollusca: Bivalvia	5–12.5 ppt (85.7–64.3%)	NA	I, IV-V	IV-V
Perna canaliculis	Mollusca: Bivalvia	12–18 ppt (65.7–48.6%)?	NA		
Aulacomya maoriana	Mollusca: Bivalvia	23 ppt (34.3%)	NA		
Austrovenus stutchburyi	Mollusca: Bivalvia	20 ppt (42.9%)	Survive, but lose weight in 14 ppt (60%)		
Sypharochiton pelliserpentis	Mollusca: Polyplacophora	17 ppt (51.4%)	Survives 3.4 ppt (90.3%) for 10 h	III-VI	nil

Species	Major group	Field seawater tolerance: salinity (ppt) and percent (%) freshwater	Experimental or other species' freshwater tolerances (10-20 °C, where available): salinity (ppt) and percent (%) freshwater	Batham (1965) zones	Boyle et al. (2001) zones
Haliotis iris	Mollusca: Gastropoda	25 ppt (28.6%)?	Continue to grow at 20 ppt (42.9%)		
Turbo smaragdus	Mollusca: Gastropoda	30 ppt (14.3%)?	NA		
Diloma subrostrata	Mollusca: Gastropoda	17 ppt (51.4%)	Survives indefinitely @ 18 ppt (48.6%)		
Cellana ornata	Mollusca: Gastropoda	25 ppt (28.6%)	50% survive 86 h @ 20 ppt (42.9%)	V	VI (rare)
Elminius modestus	Crustacea: Cirripedia	5–19 ppt (85.7–45.7%)?	5–6 ppt (85.7–82.9%)	I-VI	III-V
Chamaesipho columna	Crustacea: Cirripedia	5–13 ppt (85.7–62.9%)	NA	IV	VI
Hemigrapsus sexdentatus	Crustacea: Brachyura	14 ppt (60%)	Survives 3 d @ 0 ppt (100%)		
Hemigrapsus crenulatus	Crustacea: Brachyura	10 ppt (71.4%)	Survives >7 d @ 12 ppt (65.7%)	I-II, V	I-II (rare)
Metacarcinus novaezelandiae	Crustacea: Brachyura	25 ppt (28.6%)?	Survives >4 h @ 19 ppt (45.7%)		
Helice crassa	Crustacea: Brachyura	4 ppt (88.6%)	Survives 7 d @ 3.5 ppt (90%)		
Petrolisthes elongatus	Crustacea: Anomura	17 ppt (51.4%)	Stress after 3 d @17 ppt (51.4%)	III, V	nil
Jasus edwardsii	Crustacea: Achelata	30 ppt (14.3%)?	15 ppt (57.1%); 50% survive 7 d @ 28 ppt (20%)		

Sea lettuce, *Ulva* spp. (e.g., *U. lactuca, U. pertusa*, *U. procera*)

The genus *Ulva* L. (Ulvaceae, Ulvales, Chlorophyta), commonly known as sea lettuce, is found throughout the world, and are notoriously difficult to identify to species level because of their high phenotypic plasticity and the lack of morphological characters sufficient to separate many taxa (NIWA 2007). These green algae appear to tolerate significant freshwater influence, being common in estuaries (Jones and Marsden 2005) and within the low salinity layer in both estuaries and upper fiords at salinities as low as 5–29 ppt (Grange et al. 1981; Witman and Grange 1998; Boyle et al. 2001; Murphy 2004). Choi et al. (2010) investigated specific growth rates of *U. pertusa* at salinity regimes from 5 to 40 ppt under non-limiting nutrient and light conditions and observed higher growth at intermediate levels of salinity (15–34 ppt) and lower growth at extreme low and high salinity (<15 and >34 ppt).

Neptune's necklace, *Hormosira banksii*

This alga is common and often abundant on more sheltered rocky and boulder shores on Banks Peninsula and tolerates substantial exposure to reduced salinities. In particular, it is common in low salinity habitats in Fiordland where it is often abundant within the low salinity layer at salinities ranging between 5 ppt and >27 ppt (Grange et al. 1981; Boyle et al. 2001).

Bladder kelp, *Macrocystis pyrifera*

Macrocystis pyrifera is a common Pacific alga, found from 37 to 55 °S in bays open to the open ocean, as well as in harbours and bays that are protected from strong wave action. The effect of salinity on this large, brown seaweed has not been studied, but it has been suggested that kelp tolerate seawater dilution of almost one-third (Buschmann et al. 2004). Within its range in southern Chile, it survives salinities between 28 ppt and 33 ppt in exposed locations and between 22 ppt and 31 ppt in more sheltered situations.

Sargassum weed, *Sargassum sinclairii*

Experimental investigations show that the common Chinese species of *Sargassum* survives exposures to substantially dilute seawater, as does *S. muticum* (Chu et al. 2012). Most (90%) germlings of *S. thunbergii* survived two eight-hour exposures to 12 ppt per day. These authors also considered that the tolerance of seaweeds to salinity stress increases with age for algae generally (Norton 1977; Steen 2004). We expect that this tolerance of low salinity exposure is true for most other low-shore, brown seaweeds (e.g., *Carpophyllum maschallocarpum*, *Ecklonia radiata*, *Halopteris* spp., *Cystophora* spp.) on Banks Peninsula shores.

Bull kelp, *Durvillaea antarctica*

This large brown alga was reported at Batham's (1965) and Boyle et al.'s (2001) most seaward sites, where surface salinities were c. 31 ppt. Batham (1965) considered that water movement limited the distribution this alga.

Red algae

Estuarine and upper intertidal algae generally have a broad tolerance to salinity change (Russell 1987), and can often tolerate short-term changes in salinity without complete osmotic adjustment (Kirst 1989; Reed 1990).

Karengo, *Porphyra columbina*

A north Pacific species of *Porphyra*, *P. torta*, ranges across salinity-stable (30 ppt) outer coast environments to more sheltered shores where salinities fluctuate seasonally to 10 ppt or less (Conitz et al. 2001). Experiments on this and two other species (*Porphyra abbottae*, *P. pseudolinearis*) demonstrated no effect of salinity on survival and growth at salinities of 20–40 ppt and growth inhibition at 10 ppt (Stekoll et al. 1999). Another species (*P. pujalsii*), however, apparently occurs only where mean salinities are >20 ppt (Coutinho and Seeliger 1984).

There is no reason to expect that New Zealand's *P. columbina* will differ appreciably in its tolerance of considerable contact with dilute seawater; its peak growing season is autumn-winter, when it is exposed to substantial wetting by rain in its upper-shore habitat without apparent adverse effects.

Kina, *Evechinus chloroticus*

Experimental investigation revealed that larval development of *Evechinus chloroticus* was incomplete in salinities <28 ppt, indicating extreme sensitivity at this critical life-stage (Antonie 2003). Adult *E. chloroticus* held at salinities of 30–35 ppt all remained responsive to touch and alive after 48 hours (Antonie 2003). Adults become unresponsive after 24 hours in 25 ppt and 28 ppt, and all die after 48 hours at these salinities (Antonie 2003). Consistent with this, *E. chloroticus* was most abundant immediately below the low salinity (5–12.5 ppt) layer in Doubtful Sound (McShane and Naylor 1991, Wing et al. 2001; Miller and Abraham 2011), migrating up to access abundant food at shallower depths when the low salinity layer shallowed and down when it deepened (Witman and Grange 1998). In Doubtful Sound, its peak abundance at 5 m depth at all times placed it in full seawater (33–35 ppt) (Witman and Grange 1998). Lamare (1997) considered that periodic low salinity fluxes is a significant cause of kina mortality, particularly for juvenile kina in Doubtful Sound (Lamare and Barker 2001).

Sea stars, *Patirilella regularis* and *Coscinasterias calcamaria*

These predatory sea stars are a common intertidal to low shore inhabitants throughout New Zealand (Morton and Miller 1968), but appear to avoid low salinities. In Doubtful Sound, both species were most abundant in near-full seawater, immediately below the halocline (5 m depth) and migrated shallower when the halocline shallowed (Witman and Grange 1998). *Coscinasterias* seemed to avoid entering lower salinity waters in Doubtful Sound and elsewhere in Fiordland's stratified waters (Witman and Grange 1998; Grange et al. 1981). *Patiriella*, in comparison, appears to tolerate some brackish water exposure; in Fiordland some individuals were always present above the halocline (5–12.5 ppt), although apparently actively moving deeper (Witman and Grange 1998) and it is restricted to high salinity, seaward portions of the Avon-Heathcote Estuary (Jones and Marsden 2005).

Detailed experimental tracking of *C. muricata* in Doubtful Sound revealed that it can move fast enough to track the bottom of the low salinity layer as the tide moved in and out (Channon 2010). When the tide was high and the bottom of the mussel band was exposed to full salinity sea water these sea stars were able to feed on the mussels and still escape the low salinity layer as the tide moved out (Channon 2010). Laboratory observations that indicate that *C. muricata* cannot tolerate exposure to reduced salinities (<25 ppt), with 100% mortality occurring within 6 hours of immersion in 15 ppt and within 29 hours if exposed to 20 ppt (Lamare et al. 2009).

Tube worms, *Pomatoceros caeruleus*

Limited information within Grange et al.'s (1981) survey of Fiordland benthos indicates that *Pomatocerus caeruleus* is abundant only below (>4 m depth) persistent low salinity waters. Similarly, the disappearance of this sedentary filter-feeder from intertidal habitats in Doubtful Sound after increased freshwater discharges and a more persistent low salinity layer associated with the Manapouri power scheme (Boyle et al. 2001) indicated that it cannot tolerate persistent salinity regimes of 18–27 ppt or lower.

Blue mussels, *Mytilus galloprovincialis*

Blue mussels occurred at various salinity ranges in Wellington Harbour: 31–35 ppt to seaward; 19–30 ppt at an intermediate site; and 12–30.5 ppt at a more estuarine location with mean minimum salinities of 23 ppt (Gardner and Kathiravetpilla 1997; Lachowicz 2005). *Mytilus galloprovincialis* were the most abundant sessile inhabitants of the persistent low salinity layer (5–12.5 ppt) at 1.5–4 m depth within Doubtful Sound and elsewhere in Fiordland, covering up to 80% of rock surfaces (Grange et al. 1981; Witman and Grange 1998; Boyle et al. 2001).

Green-lipped mussels, *Perna canaliculus*

As with blue mussels, green-lipped mussels occurred at different salinity ranges within Wellington Harbour: 31–35 ppt to seaward; 18.9–30 ppt at an intermediate site; and 12–30.5 ppt at the most estuarine location (Gardner and Kathiravetpilla 1997; Lachowicz 2005). In Marlborough Sounds, these mussels are farmed at sites with salinities ranging between 20 ppt and 35 ppt (Gibbs et al. 1991).

Species belonging to the genus *Perna* tolerate wide fluctuations in salinity (e.g., *P. viridis* tolerates salinities ranging from 5–40 ppt (Rajagopal et al. 1998)), but salinities below 5 ppt are lethal to *P. viridis* if exposure exceeds 2 days (Coeroli et al. 1984).

Ribbed mussels, *Aulacomya maoriana*

Ribbed mussels also tolerate considerable freshwater dilution of seawater. Lachowicz (2005) found *Aulacomya maoriana*, along with blue and green-lipped mussels at sites with mean minimum salinities as low as 22–23 ppt in Wellington Harbour. They also inhabited the shallow (0–3 m depth) low salinity layer (salinities not measured) in parts of Fiordland (Grange et al. 1981).

Little black (flea) mussel, *Limnoperna pulex*

In New Zealand, *Limnopulex pulex* ranges from open exposed rocky shores to semi-sheltered shores (Morton and Miller 1968). It occurred along the entire length of Doubtful Sound in 1960–63 in surface salinities ranging from 3–28 ppt (Batham 1965). In 1995, after commencement of flows from the Manapouri Power Station, this small mussel was present only at more seaward stations where reported salinities were >18 ppt (Boyle et al. 2001).

No specific salinity tolerance data were found for this species. However, Wilson (1968) examined salinity tolerances of another species, *L. securis* (occurs in NZ). In the Swan River estuary (Western Australia), populations were exposed to salinities as low as 1 ppt, sometimes for as long as 2–3 months, and over 20 ppt during summer, surviving large changes (e.g., 6–19 ppt) within 4 days. Experiments confirmed these field observations, and showed 100% survival of adult *L. securis* after 4 months' immersion in 1–2 ppt seawater (Wilson 1968).

Tuatua, *Paphies donacina*

These surf clams in inhabit sandy beaches throughout the region, including a few bays on Banks Peninsula. The ability of tuatua to survive seawater dilution is poorly understood. Two mass strandings of tuatua, one on Te Waewae Bay (Southland) and another on South Brighton Beach were attributed to freshwater inundation from adjacent flooding rivers (Eggleston and Hickman 1972; Fenwick and Ogilvie 2001). The actual salinities of waters potentially causing these strandings was not determined.

Cockles, *Austrovenus stutchburyi*

The intertidal clam, *Austrovenus stutchburyi*, is an important mahinga kai and recreational shellfish within inner reaches of Akaroa Harbour and at Okains Bay on Banks Peninsula (Bolton-Ritchie 2005a, 2008a). It is quite euryhaline, withstanding at least 6 weeks' immersion in dilute (20 ppt) seawater at 15°C (Marsden 2004). Its survival in low seawater concentrations varies with food availability, but, with high phytoplankton availability (>20µg chlorphyll-*a*/L), some clams survived at 7 ppt for 6 weeks (Marsden 2004).

Snake-skin chiton, *Sypharochiton pelliserpentis*

This ubiquitous chiton inhabits open coast to estuarine and harbour shores. Experiments reveal that it is quite euryhaline, with 80–85% survival in 50% (17 ppt) seawater after 24 hours at 10°C, and 100% survival at 20°C (Boyle 1969). Immersion in freshwater (0% seawater) caused significant mortality only after 10 hours at 10 °C and 20 °C. Based on these observations, we expect that *Sypharochiton pelliserpentis* will readily tolerate exposure to salinities of 20–25 ppt for several days at a time.

Originally abundant and widespread in Doubtful Sound, it was largely absent after the Manapouri power scheme increased freshwater outflows into the sound (Boyle et al. 2001). Batham (1965) reported this chiton as present to abundant at her four seaward regions, whereas Boyle et al. (2001) failed to locate it in any region, attributing this change to more extreme continual dilution of surface waters (Boyle et al. 2001: 670).

Paua, *Haliotis iris* and *H. australis*

Salinity tolerances of New Zealand paua are poorly known. The species characteristically inhabits open coasts and semi-sheltered situations, where full salinities predominate. Grange et al. (1981) reported *Haliotis virginea* as part of the mobile epifauna at 0–4 m depth in an area of Fiordland where the low salinity layer reached to at least 3 m depth. Salinities were not measured as part of that study, so this report indicates only that *H. virginea* can withstand some seawater dilution, but it probably actively migrates deeper whenever exposed to reduced salinity.

Information on salinity tolerances from other species in the genus *Haliotis* provide some insight into likely tolerances of seawater dilution by New Zealand species. Juveniles (c. 40 mm) of green-lip (*H. laevigata* Leach) and black-lip (*H. rubra* Leach) abalone from Tasmania survived a single abrupt change from seawater to 25 ppt for at least 3 days (Edwards 2003). Typical salinities for mid-shore to subtidal habitats for red abalone (*H. rufescens*) and black abalone (*H. cracherodii*) along the California coast were 32–35 ppt, and both species may be exposed to salinities as low as 25 ppt during high rainfall seasons (Martello et al. 1998). Experiments on their physiological responses to PCP exposure showed that these abalone survived 3.5 and 6.5 hour exposures, respectively, for red and black abalone to salinities of 25, 35 and 45 ppt (Martello et al. 1998).

Experiments demonstrated that for *Haliotis tuberculata* growth was not affected at salinities between 29 ppt and 38 ppt, but their growth rates decreased at 26 ppt (Basuyaux and Mathieu 1998). *Haliotis varia* died within 5 days if the salinity gradually reduced to 15 ppt (Kaligis and Lasut 1997).

The Taiwan abalone, *Haliotis diversicolor supertexta*, survived more than 9 days when transferred from 33 ppt seawater to salinities as low as 23 ppt (Cheng et al. 2002). In further experiments, the lowest salinity at which all juveniles survived (remained responsive to tactile stimulus after 96 hours) was 17 ppt at 20°C and 15 ppt at 25°C (Chen and Chen 2000). In experiments on growth when fed artificial diets, this species survived a daily (within 24 h) salinity change to 16 ppt, survived retention at 20 ppt, and continued to grow at salinities of 25–35 ppt (Changsheng et al. 2000). Similarly, juveniles (20–25 mm) of *H. asinia* (Thailand) tolerated salinities as low as 20 ppt without acclimation, and as low as 12.5 ppt with gradual lowering of salinity over 2 days (Singhagraiwan et al. 1992).

Based on these studies, we expect that the New Zealand species of *Haliotis* probably withstand dilution of seawater to 30 ppt and probably considerably lower, especially if the reduction is gradual. Also, these large gastropods rapidly move away from predators, indicating the potential to migrate into deeper, more saline water when immersed in diluted seawater.

Ornate limpet, *Cellana ornata*

Salinity tolerances of this common New Zealand limpet or of any other New Zealand representative of this widespread genus, appear poorly known. It dominates on many open rocky shores, as well as penetrating well into harbours (e.g., Akaroa Harbour; Fenwick 2004) and even into some estuaries (Jones and Marsden 2005). It was not present at inner, freshwater dominated sites within Doubtful Sound, but present only at seaward locations where surface salinities were 25 ppt (Batham 1965; Boyle et al. 2001).

At least one species of *Cellana*, the tropical *C. radiata* (not *C. radians*), tolerates immersion in significantly diluted seawater. Rao and Ganapati (1972) found 50% mortality of this species when immersed in 20 ppt seawater for 84–96 hours.

Cats eyes, *Turbo smaragdus*

This herbivorous gastropod snail was reported from within or just below the low salinity layer in Fiordland, indicating some tolerance of at least temporary reduced salinities (Grange et al. 1981) and/or some behavioural adaptation to lowered salinities.

Mudflat top shell, *Diloma subrostrata*

Diloma subrostrata, a soft-shore, trochid gastropod, lives mostly between 0.8 m and 1.4 m above LWS, mostly on hard substrata (Logan 1976). At high water it is typically exposed to salinities of c. 34 ppt, but, in many places, it may be exposed to low salinities (9–13 ppt) during low tides (Logan 1976). However, preliminary laboratory experiments showed that this snail cannot survive indefinitely at salinities below 50% (17 ppt) seawater.

The related species, *Diloma zelandica*, apparently tolerates similar variation in salinities, being found within or close to the lower salinity layer at 0–4 m depth in parts of Fiordland (Grange et al. 1981).

Estuarine barnacle, *Elminius modestus*

Adult *Eliminius modestus*, like many other intertidal barnacles, are euryhaline; tolerant, after acclimation, of salinities down to c. 5–6 ppt seawater (Foster 1970; Cawthorne 1978). It inhabits the intertidal and 0–3 m depth, lower salinity layer in Fiordland (Batham, 1965; Grange et al. 1981), occurring abundantly at sites exposed to salinities of 5–19 ppt (Boyle et al. 2001). It penetrates well into many New Zealand harbours and estuaries where they are frequently exposed to very strong freshwater influence (e.g., Batham 1965; Morton and Miller 1968; Jones and Marsden 2005). Larvae of this barnacle also are very tolerant of seawater dilution: they survive abrupt changes in salinity with minimal mortality, so long as the change is into >25% seawater (c. 9 ppt) (Cawthorne 1978).

Acorn barnacle, *Chamaesipho columna*

This barnacle is very abundant on Banks Peninsula's outer coasts and many harbour shores, where it forms dense mats over mid-shore rock surfaces (e.g., Knox 1953; Fenwick 2003, 2004). Barnacles (mostly *Chamaesipho columna*) covered 17–21%, on average, of 0–3 m depth rock surfaces at two Fiordland locations where salinities were 5–12.5 ppt (Witman and Grange 1998). Salinity tolerances for this species are not otherwise known.

Rock and shore crabs, *Hemigrapsus sexdentatus* and *H. crenulatus*

The purple rock crab *Hemigrapsus sexdentatus* (formerly *H. edwardsii*) and hairy-handed shore crab *H. crenulatus* are euryhaline intertidal crabs endemic to New Zealand, where they are common at mid-tide levels. One, *H. sexdentatus*, is more common of moderately exposed, rocky shores, whereas the other, *H. crenulatus*, is more commonly associated with fine sediments on sheltered shores and well into many estuaries (Bennett 1964; Hicks 1973; McLay 1988; Jones and Marsden 2005). Within the Avon-Heathcote Estuary, *H. crenulatus* was found at sites where lowest recorded salinities were 17 ppt or higher (Jones 1976).

Adults of both species readily withstand their exposure to rainfall at low tide and their frequent occurrence near to freshwater streams and, in the case of *H. crenulatus*, within estuaries (Seneviratna and Taylor 2006). They are commonly found at salinities as low as 14–15 ppt (Hicks 1973). *Hemigrapsus sexdentatus* survived at least 8 days when fully immersed in 15 ppt seawater at 5, 15 or 25°C in winter (i.e., adapted to prevailing lower temperatures), but only at 15°C in summer (Hicks 1973). Similarly, winter-adapted *H. crenulatus* survived well regardless of temperature, whereas summer-adapted individuals survived the full 8 days in 15 ppt only at 5 or 15 at 5–25°C (Hicks 1973). In a separate study, *H. crenulatus* was found to survive seven days' immersion in 50% (c. 17 ppt) seawater, tolerate 10% seawater well, and survive 1% (c. 0.3 ppt) seawater for at least 7 days (Jones 1976).

Embryos (gastrulation to hatching) of both species survived immediate transfer to 1% seawater for several days without significant mortality or obvious impairment of development (Taylor and Seneviratna 2005).

Pie-crust crab, *Metacarcinus novaezelandiae*

This large crab, abundant within Banks Peninsula's larger harbours, inhabits estuaries to open coast shores, living under rocks, on wharf piles and amongst algae from the lower intertidal to perhaps 40 m depth (McLay, 1988), often associated with muddy sediments. As suggested by its habitat range, the pie crust-crab survives in diluted seawater (55% or c. 19 ppt) for at least 4 hours (East and Petersen, 1967 *in* McLay 1988).

Mud crab, *Helice crassa*

Extremely abundant on mudflats within Banks Peninsula's large harbours and other estuaries, *Helice crassa* is characteristic of habitats with strong freshwater influences (McLay 1988). It excavates permanent burrows within muddy sediments, from which it forages at low tides (Jones 1976). It is euryhaline, usually not limited by salinity and, within the Avon-Heathcote Estuary, its distribution spans areas where low water salinities range between 1–28 ppt, and high water salinities of 35 ppt (Jones 1976). At its inland extremes within the Avon-Heathcote, *H. crassa* populations experience salinity ranges of 1–26 ppt and 4.5–32 ppt (Jones 1976).

In lab experiments, summer-adapted crabs survived 7 days in salinities of 3.5–52.5 ppt at temperatures of 5–30°C (Jones 1981). Juvenile crabs had wider salinity tolerances than adults, but newly released larvae (stage 1 zoeae) were stenohaline, all dying within 1 hour's exposure to salinities of 3.5–10.5 ppt and within 24h in 14 ppt (no mortality in 35 ppt) (Jones 1981).

Blue false crab, *Petrolisthes elongatus*

Huge numbers of these usually dark green crabs occur on sheltered rocky shores around Banks Peninsula (e.g., McLay 1988; Fenwick 2003), wherever it's highly specific mix of stone-cobbles-boulders is found (Jones 1976). In contrast to true crabs, *P. elongatus* is stenohaline (Jones 1976); in Avon-Heathcote Estuary, it occurred only at sites where salinities remain above about 17 ppt (Jones 1976). It shows stress after 3 days in 17 ppt seawater or immediately in 3.5 ppt or more dilute seawater.

Rock lobster/koura, *Jasus edwardsii*

Rock lobsters apparently avoid low salinity environments at 0–4 m depth in Fiordland, even when these offer abundant food (Witman and Grange 1998). Instead, they appear restricted to 4–10 m depths (Grange et al. 1981). Pueruli of rock lobsters do not tolerate salinities below 26 ppt (Booth and Kittaka 2008). Juvenile *J. edwardsii* tolerate salinities between 25 ppt and 36 ppt, and develop best at 33 ppt (Jeffs and Hooker 2000). Adults tolerate abrupt changes of c. 5 ppt, but immediate reductions to 25–28 ppt resulted in 50% mortality and 100% mortality with a change to 20 ppt in one small investigation (Stead 1973). They survive much lower salinities (as low as 15 ppt) if incremental changes are small (<5 ppt) and there is an acclimation period between changes (Stead 1973). Stead's (1973) observations during these experiments showed reduced activity of lobsters held at lower salinities and that lobsters' abdominal segments (ventral surfaces) swelled when individuals experienced abrupt salinity changes >10 ppt.

Chinook salmon (=quinnat, king or spring salmon), *Onchorynchus tshawytscha*

Salmon display remarkable osmoregulatory abilities consistent with their anadromous life-history – they hatch in freshwater, spend most of their life in the sea and return to freshwater to spawn). This life-history is reflected in their salinity preferences (i.e., freshwater for eggs and parr, lower salinity for smolt migrating to seawater, full-strength seawater for post-smolts and yearlings, and reducing salinity for sexually mature fish about to return to freshwater (Oppedal et al. 2011)).

Sea-cage culture places salmon in a complex natural and artificial environment where their movements are restricted by cage nets and the surface. Salmon farms located in bays, sounds, harbours (e.g., Akaroa Salmon New Zealand Ltd in Lucas Bay Akaroa Harbour) or fjords may experience greater variation in environmental conditions within with strong vertical stratification variations in salinity, temperature, oxygen and water currents (Johansson et al. 2007; Oppedal et al. 2011). Behavioural trade-offs in response to environmental drivers may result in schooling at specific depths, which may alter depth-specific stocking densities and, consequently, affect salmon welfare (Oppedal et al. 2011). Salinity appears unimportant in determining vertical distributions in sea-cages of >3 month-old, sexually immature seawater-transferred Atlantic salmon (*Salmo salar*) and do not generally affect non-migratory stages (Oppedal et al. 2011). However, newly transferred smolts do prefer the depth of the halocline. Water temperature appears to be the strongest driver of vertical distributions in sea-cages for this species (Oppedal et al. 2011).

Atlantic salmon smolts survived 3–6 weeks at 0 ppt and 10 ppt and their ability to tolerate low salinities increased by 5–6 weeks. Atlantic salmon smolt survival was unaffected at salinities of 0, 10, 20 and 31 ppt and there was some growth-retardation at salinities >20 ppt (Duston 1994). Bakke et al. (1991) found that abrupt artificial salinity changes from 34 ppt to 10 and 5 ppt in post-smolt Atlantic salmon did not affect salmon mortality, but that abrupt salinity changes in combination with other environmental factors may stress post-smolt salmon. Reduced salinities (particularly <20 ppt) may benefit salmon affected by sea lice because these crustacean pests cannot tolerate significantly reduced salinity (Oppedal et al. 2011).

3.3.3 Salinity impacts summary

Indicative salinity minima for marine species inhabiting sheltered to open shores on Banks Peninsula (or closely related taxa), indicate that most species will tolerate short-term exposure to 30 ppt seawater, and that algae and many invertebrates, including rock lobsters, withstand even greater dilutions (down to 25 ppt). Mid to upper shore algae and invertebrates are generally euryhaline, tolerating greater salinity dilution. Survival of longer-term (10–40 day) exposures to these salinities is generally uncertain.

Thus, modelled seawater dilutions from Lake Ellesmere openings alone (section 3.3) appear unlikely to have any major direct effect on benthic invertebrates and algae around coastal Banks Peninsula, or on farmed salmon in Akaroa Harbour. Larger mobile invertebrates and fishes are expected to actively migrate away from low salinity waters, generally by moving to a greater depth. Modelling indicates that the Rakaia and other rivers south of Banks Peninsula naturally produce greater dilution to a greater depth and, therefore, would have a greater potential freshwater impact on the benthic biota than the artificial openings of Lake Ellesmere.

4 Discussion

4.1 Modelling Lake Ellesmere freshwater

Hydrodynamic modelling confirms that coastal waters along Banks Peninsula's southern coast are diluted less by the Lake Ellesmere freshwater plume and over a smaller area than that of the combined riverine freshwater discharges from east coast rivers of the South Island south of Banks Peninsula (Hadfield and Zeldis 2012). Similarly, the depth of dilution of Banks Peninsula coastal water by Lake Ellesmere water is no greater than that resulting from naturally-driven outflows of freshwaters from other riverine sources within Canterbury Bight.

Model results indicate that the Lake Ellesmere dilution plume may extend around the peninsula as far as Putakolo Head (Hickory Bay), diluting surface coastal waters (undiluted c. 34 ppt) eastward to this point by up to c. 4–7% (to c. 31 ppt). Surface waters at the entrance to Akaroa Harbour were diluted to this extent, surface water at the middle Akaroa Harbour station was diluted very slightly (reduced by 1–3 ppt), and the inner station was even less affected. At sites closest to Lake Ellesmere, the freshwater plume is generally concentrated in the top 5–10 m of seawater with distinct stratification. As we move further away from Lake Ellesmere around Banks Peninsula, the freshwater plume in surface waters becomes more vertically mixed.

Unpublished CTD data for 13 stations along the midline of Akaroa Harbour from its shallow inner reaches to outside the heads (NIWA files, eight dates, Oct 1996–Dec 1998) confirm these modelling results. Generally, there was no marked stratification of the water column, especially over the surface five metres. Any stratification over this depth range involved salinity changes of no more than 1 ppt, with one anomalous exception.

4.2 Ecological effects of Lake Ellesmere plumes

Most intertidal and shallow subtidal, benthic species appear able to tolerate abrupt dilution of seawater to c. 30 ppt, greater than the c. 5% modelled dilution (i.e., to c. 32–33 ppt) by Lake Ellesmere water reaching the outer coast of Banks Peninsula. Based on this, we conclude that surface water dilution by openings of Lake Ellesmere alone will not have a significant adverse effect on the biodiversity and ecology of Banks Peninsula. Certainly, dilution of these waters from this source is considerably less than that from other contributing river sources around Banks Peninsula and the south east of the South Island (Hadfield and Zeldis 2012). Hadfield and Zeldis (2012) identified the Rakaia River as the single source that produced the highest freshwater concentrations in surface seawater around Banks Peninsula. Indeed, freshwater dilution of surface waters around Banks Peninsula by the Rakaia River alone was almost always greater than that of Lake Ellesmere following openings during modelled periods in 2009 and 2011 (Hadfield and Zeldis 2012 and Figures 9–11 this report).

We note three caveats, however. First, Lake Ellesmere water contains elevated concentrations of nutrients, phytoplankton, and other substances that may directly or indirectly impact Banks Peninsula's coastal ecosystem. Second, the modelled results of this report indicate the potential for Lake Ellesmere water, alone or in combination with water from other east coast sources, to vertically density-stratify the coastal water column. Such conditions have the potential to establish favourable conditions for harmful or other phytoplankton blooms. Third, dilution of coastal waters by Lake Ellesmere water, major rivers and terrestrial runoff, cumulatively, may adversely affect the Banks Peninsula ecosystem.

It should be possible, in any future work, to model total vertical freshwater dilution at each of the eight specified representative coastal sites around Banks Peninsula for all freshwater inputs (i.e., lake, river and terrestrial runoff) following Lake Ellesmere openings. Hadfield and Zeldis (2012) did model total freshwater dilution (eight freshwater tracers) over a 365-day period from 21 April 2009 to 21 April 2010 (the same period as the first simulation analysed in this report) at two sites around Banks Peninsula (one near Akaroa Harbour entrance and the other at Lyttelton Harbour/Port Levy entrance). The annual mean freshwater concentration near Akaroa Harbour entrance from that simulation was c. 1–3% (0.35–1.05 ppt reduction) between 0–10 m depth, with maximum dilutions to c. 5–28% freshwater (salinities = 24.2–32.3 ppt) largely associated with shallow Rakaia River freshwater plumes. The Lyttelton Harbour/Port Levy entrance site had much lower freshwater concentrations.

Seawater/lake water exchange during Lake Ellesmere openings can be substantial causing elevated lake salinity, resulting in brackish conditions (Larned and Schallenberg 2006; Horrell 2008; Spigel 2009; Kitto 2010), with a mean salinity of 7 ppt (range 2.3–14.2 ppt) observed between 1993 and 2005 (Schallenberg et al. 2010). Our modelling assumed that all water flowing from the opened lake comprised pure freshwater (0 ppt). This approach means that the modelled dilutions due to lake water over-estimated seawater dilutions at all sites. Thus, future modelling could incorporate actual or modelled (i.e., Spigel 2009) lake salinities.

4.3 Possible impacts of nutrients and other contaminants entrained within Lake Ellesmere plumes

4.3.1 Nutrients and freshwater phytoplankton

Lake Ellesmere is a shallow, brackish, turbid, hyper-eutrophic lake (Kitto 2010; Schallenberg et al. 2010). Its hyper-eutrophic state is often attributed to the development of surrounding agriculture and the lake's current shallow, wind-mixed state: wind-mixing re-suspends lake sediments and nutrients, leading to high phytoplankton productivity with cyanobacteria and Chlorophyta dominating (Kitto 2010).

Terrestrial inputs and freshwater discharges into the coastal marine environment are major contributors to marine ecosystem functioning, productivity and carbon/nitrogen cycles (e.g., Ludwig et al. 2009; Morrison et al. 2009). In nutrient-limited coastal waters, these inputs/discharges can have beneficial effects (e.g., increased nutrient-delivery to organisms and enhanced primary productivity (Nixon et al. 2002; Zeldis et al. 2008)). However, excessive nutrient and particulate discharge can accelerate coastal eutrophication and lead to adverse effects (e.g., problematic algal blooms, oxygen depletion, benthic community changes etc.: NRC 2000; Cloern 2001), whilst reductions in nutrient discharge can lead to oligotrophication, with its own adverse effects (e.g., reduced primary productivity and subsequent effects on fish and shellfish stocks (Smith et al. 1999; Cloern 2001; Zeldis et al. 2008; Paerl 2009)).

The main nutrient sources for Lake Ellesmere are the lake tributaries (five main rivers and 32 drains), groundwater and seawater intrusions (Larned and Schallenberg 2006; Kitto, 2010; Schallenberg et al. 2010; Clark 2011). Larned and Schallenberg (2006) demonstrated the dynamic nature of nutrient (i.e., Dissolved Reactive Phosphorous (DRP), Total Phosphorous (TP), Dissolved Inorganic Nitrogen (DIN), and Chlorophyll-*a*) concentrations in Lake Ellesmere, with a high degree of nutrient variability on short (e.g., monthly) time scales. Lake water quality responds weakly to lake opening and closing events, indicating overall inadequate tidal flushing of the lake (Schallenberg et al. 2010).

Environment Canterbury has assessed coastal nutrient concentrations of nitrogen- and phosphorous-based determinands (ammonia-nitrogen (NH_3-N), nitrate-nitrite nitrogen (NNN), total nitrogen (TN), DRP and TP), chlorophyll-*a* and total suspended sediments around Banks Peninsula. Coastal water quality sampling from November 2001 to June 2002, and July 2006 to June 2007 (two lake openings in 2001, five in 2002, three each in 2006 and 2007: Spigel 2009 appendix A-1) in selected bays around Banks Peninsula, showed that nutrient concentrations were comparable to those reported from sites north and south of Banks Peninsula, but that there was considerable spatial and temporal variability in all water quality variables measured (Bolton-Ritchie 2008b). All NH_3-N concentrations were below the ANZECC (2000) trigger value (0.5 mg/L) providing protection for 99% of marine species. Rainfall (i.e., stream inflow and general land run-off), bay aspect/length, bay hydrodynamics and wave re-suspension of sediments were the significant contributors to coastal water quality (Bolton-Ritchie 2008b). Although not specifically investigated, there did not appear to be any general trend in coastal nutrient and phytoplankton concentrations in Bolton-Ritchie's (2008b) results that reflected proximity to Lake Ellesmere. Bolton-Ritchie (2005b) found the nutrient concentrations in Akaroa Harbour water between April 1989 and June 2004 generally lower than those in Lyttelton Harbour and nitrogen-based nutrient concentrations lower than, and phosphorous-based nutrient concentrations comparable to, those of Pegasus Bay.

A "biological" version of the hydrodynamic model used for this investigation could be used to further examine the fate of nutrients, sediments and freshwater phytoplankton within Lake Ellesmere water. Data available within NIWA and from Environment Canterbury (e.g., Banks Peninsula river and stream water quality, coastal water quality, etc.) would comprise useful inputs to this model and greatly assist in further elucidating potential effects of lake openings on the coastal marine environment and its associated values.

4.3.2 Contaminants and undesirable organisms

Bacteria

Several bacteria are used as indicators of water contamination. These indicator species are used on the assumption that, where they are rare, other harmful bacteria (e.g., Campylobacter) and harmful micro-organisms (e.g., Cryptosporidium) are also likely to be rare (Davies-Colley and Wilcock, 2004; Chigbu and Sobolev, 2007). The most commonly monitored indicator bacteria are ordinary bacteria which live inside humans and other mammals and usually exit with their faeces – enterococci and faecal coliform bacteria. Faecal coliforms, and their main constituent species *Escherichia coli*, are used to define the water quality classes in the Water and Soil Conservation Act 1967, and enterococci are used in the Department of Health 1992 guidelines for bathing and shellfish gathering (source: http://www.mfe.govt.nz).

Environment Canterbury monitors Lake Ellesmere water quality for faecal bacterial (*E. coli*) concentrations. Recent lakeside concentrations of *E. coli* are generally below trigger levels (550/100 ml), but *E. coli* concentrations at the Selwyn River monitoring site at Upper Huts are higher, and sometimes exceed trigger levels (source: http://maps.ecan.govt.nz/WaterQuality/).

Many interacting factors affect the survival of faecal indicator bacteria in seawater: nutrient availability; salinity; temperature; degree of water mixing; pH, microbial predation (e.g., protozoans), and solar radiation (Sinton et al. 2002; Chigbu and Sobolev 2007). The last factor appears to be most important, with greater, faster inactivation of faecal coliforms and enterococci at shallower depths where UV-A wavelengths penetrate (Davies-Colley et al. 1994; Sinton et al. 1999; Sinton et al. 2002). One important synergistic effect here is that sunlight inactivation of faecal indicator bacteria increases with increasing salinity (Solić and Krstulović 1992; Sinton et al. 2002).

Modelled freshwater plumes from Lake Ellesmere took longer to reach more distant sites around Banks Peninsula (Figures 3–5 and 9–11). For example, Lake Ellesmere plumes reached Site 1 (Tokoroa Bay) c. 5–8 days after lake openings, c. 5–13 days for Akaroa Harbour's entrance and c. 13 days for Lyttelton Harbour/Port Levy entrances.

Lake derived bacteria in plumes are unlikely to adversely affect the Banks peninsula ecosystem because concentrations are often below trigger levels, and they are likely to be rendered harmless by exposure to sunlight whilst entrained within surface- plumes (despite turbidity effects) and gradual dilution and mixing with higher salinity seawater. Indeed, Environment Canterbury coastal water quality sampling from November 2001 to June 2002, and July 2006 to June 2007 in selected bays around Banks Peninsula, including Tumbledown Bay and Te Oka Bay near Lake Ellesmere, revealed low enterococci concentrations within all bays – all below alert trigger concentrations of 140/100 ml for contact recreation (Bolton-Ritchie 2008b).

The lack of available information on enteric viruses or faecal bacteriophages (these are not part of Environment Canterbury's monitoring programme for Lake Ellesmere or coastal Banks Peninsula) precludes any discussion of this potential risk. However, we note that the same plume behaviour and dilution processes are likely to reduce any risk to Banks Peninsula's coastal ecosystem values.

Cyanobacteria

Cyanotoxins encompass diverse natural toxins that have a very broad range of toxicity mechanisms. The cyanobacterium *Nodularia spumigena* produces the hepatotoxin Nodularin, identified from Lake Ellesmere (Carmichael et al. 1988) and Lake Forsyth. Cyanotoxins may have significant detrimental effects on water quality, with associated hazards to human and animal health, including rendering estuarine mussels unfit for human consumption (Blackburn et al. 1996).

Environment Canterbury monitors Lake Ellesmere for cyanobacteria (*N. spumigena*) concentrations. Recent testing showed that cyanobacteria concentrations in Lake Ellesmere remain above the public health trigger levels (http://maps.ecan.govt.nz/WaterQuality/).

Blooms of *N. spumigena* occur most commonly in brackish waters, typically in estuaries or coastal lagoons, where there are high levels of eutrophication, low N/P ratios and specific environmental conditions (warm and calm weather, high irradiance, thermal stratification) (Hobson and Fallowfield

2003; Mazur-Marzec et al. 2005). One of the most important factors controlling growth and toxin production in *N. spumigena* is salinity, with optimal growth typically in the range of 5–30 ppt and significant inhibition in freshwater (0 ppt) and full-strength seawater (35 ppt) (Blackburn et al. 1996; Moisander et al. 2002; Mazur-Marzec et al. 2005). Abrupt changes in salinity exposure may also cause cell plasmolysis and sedimentation (Mazur-Marzec et al. 2005). However, strain-specific salinity tolerances can exist. For example, the Australian strain of *N. spumigena* appears to have a higher salinity tolerance than Baltic Sea strains (Blackburn et al. 1996; Mazur-Marzec et al. 2005).

Given the combination of relatively small salinity depression of Banks Peninsula coastal waters by Lake Ellesmere plumes (as described earlier), plume transit times, nutrient-limitation in coastal waters and need for other specific environmental conditions, it seems unlikely that any *N. spumigena* entrained with Lake Ellesmere plumes would present a blooming threat to coastal Banks Peninsula. However, there remains a small possibility that *N. spumigena* in Lake Ellesmere poses a threat to coastal ecosystem values because it could be a strain with some physiological adaptations and/or environmental tolerances predisposing it to blooming under conditions that develop within Lake Ellesmere water plumes.

5 Conclusions

1. Lake Ellesmere (Te Waihora) discharges up to an estimated 250 m^3/s and 132 m^3/s on average when opened (Horrell 2008), but flows vary with tidal cycle and duration of the opening as the lake level falls. Thus, following an initial period of 10–12 days post-opening (mean peak discharge = 180 m^3/s), subsequent discharges comprise a mix of seawater and lake water.
2. In comparison to Lake Ellesmere discharges following openings, the Rakaia River's mean discharge to the sea was estimated at 211 m^3/s, with floods discharging >5600 m^3/s , over the entire tidal cycle. Thus, Lake Ellesmere may contribute up to 38.5% to the mean freshwater discharge from both sources and a smaller percentage (34.4%) of the combined mean discharges of all rivers within the Canterbury Bight. Notably, peak discharge from Lake Ellesmere is just 4.5% of the Rakaia's peak discharge.
3. Also, the Rakaia's discharge exceeds 300 m^3/s about 14% of the time and Lake Ellesmere's peak mean discharge (180 m^3/sec) 40% of the time (NIWA internal data), whereas Lake Ellesmere was open just c. 18% of the time over Sept 1990–July 2002. Thus, the Banks Peninsula coastal environment appears to be subjected to more frequent, larger scale and naturally-occurring dilution events from the Rakaia than from Lake Ellesmere.
4. Modelling confirmed that coastal waters along Banks Peninsula's southern coast are diluted less by the Lake Ellesmere plume and over a smaller area than that of the combined riverine freshwater discharges from southeast coast rivers of the South Island. Similarly, the depth of dilution of Banks Peninsula coastal water by Lake Ellesmere water is no greater than that resulting from naturally-driven outflows of freshwaters from other sources within Canterbury Bight.
5. Model results indicated that the freshwater dilution plume may extend around the peninsula as far as Putakolo Head (Hickory Bay), diluting surface coastal waters (34 ppt) eastward to this point by up to c. 4–7% (to c. 31 ppt). Surface waters at the entrance to Akaroa Harbour were diluted to this extent, surface water at the middle Akaroa Harbour station was diluted very slightly (reduced by 1–3 ppt), and the inner station was not affected. These results also indicated that this dilution was generally confined to the surface 1–5 m of the water column, below which salinities were c. 34 ppt.
6. A substantial search of literature on experiments and/or detailed field investigations determined indicative salinity minima for several species (or closely related taxa) inhabiting sheltered to open shores on Banks Peninsula. These results indicate that most species will tolerate 30 ppt seawater, and that algae and many invertebrates, including rock lobsters (Stead 1973), withstand even greater dilutions (down to 25 ppt).
7. Survival of longer-term (10–40 day) exposures to these salinities is generally uncertain. Even during longer durations, however, biota inhabiting mid tide to sublittoral depths will be inundated by potentially higher salinity water at least for a few hours daily during high tides (i.e., increased tidal water depth). Upper littoral algae and invertebrates are generally euryhaline, tolerating a far wider salinity range.
8. Larger mobile invertebrates and fishes are expected to actively migrate away from low salinity waters, generally by moving to a greater depth. Despite this, there is some evidence that rock lobsters (koura) are exposed to diluted seawater at times, but modelling indicates that discharges by the Rakaia and other rivers south of Banks Peninsula produce greater dilution to a greater depth and, therefore, have a greater freshwater impact on the coastal ecosystem.
9. In this report we focussed on salinity depression as a potential driver of marine biotic impacts on Banks Peninsula. However, we note that Lake Ellesmere water contains elevated concentrations of phytoplankton, nutrients and other organisms and substances that may directly or indirectly impact Banks Peninsula's coastal ecosystem. From modelled plume dynamics and available knowledge, it appears that nutrients,

faecal bacteria and toxic cyanobacteria in Lake Ellesmere plumes have no adverse impact on Banks Peninsula's coastal ecosystems. However, further investigations of these issues are warranted.

10. Given the modelling capability developed in this investigation to estimate plume concentration around Banks Peninsula, available data could be used to estimate the effect of Ellesmere water on coastal nutrient (e.g., NH_3N, DRP, DIN, phytoplankton) and contaminant (e.g., faecal indicator bacteria, protozoans and their cysts) concentrations and their individual and combined impacts on the coastal ecosystem.

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